



Atomic Energy
Control Board

Commission de contrôle
de l'énergie atomique

P.O. Box 1046
Ottawa, Canada
K1P 5S9

C.P. 1046
Ottawa, Canada
K1P 5S9

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DOSES FROM PORTABLE GAUGES

by

S.H. Linauskas
Atomic Energy of Canada Limited

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DOSES FROM PORTABLE GAUGES

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ABSTRACT

Field studies to measure actual radiation exposures of operators of commercial moisture-density gauges were undertaken in several regions of Canada. Newly developed bubble detector dosimeter technology and conventional dosimetry such as thermoluminescent dosimeters (TLDs), integrating electronic dosimeters (DRDs), and CR-39 neutron track-etch detectors were used to estimate the doses received by 23 moisture-density gauge operators and maintenance staff. These radiation dose estimates were supported by mapping radiation fields and accounting for the time an operator was near a gauge. Major findings indicate that gauge maintenance and servicing workers were more likely than gauge operators to receive exposures above the level of 5 mSv, and that neutron doses were roughly the same as gamma doses. Gauge operators receive approximately 75% of their dose when transporting and carrying the gauge. Dose to their hands is similar to the dose to their trunks, but the dose to their feet area is 6 to 30 times higher. Gamma radiation is the primary source of radiation contributing to operator dose.

RÉSUMÉ

Des études sur place pour mesurer les radioexpositions réelles des opérateurs de jauges commerciales de densité-humidité ont été effectuées dans plusieurs régions du Canada. De nouvelles techniques de dosimétrie à l'aide de dosimètres-détecteurs à bulles et des instruments habituels de dosimétrie, tels les dosimètres thermoluminescents (DTL), les dosimètres intégrateurs électroniques (DIE) et les détecteurs ionographiques CR-39 par capture de neutrons ont été utilisés pour évaluer les doses reçues par les 23 employés d'entretien et opérateurs de jauges de densité-humidité. Ces estimations de doses de rayonnement sont appuyées par des plans de champs de rayonnement et des calculs du temps où un employé était à proximité de la jauge. Les principales constatations révèlent que les employés chargés du service et de l'entretien des jauges risquaient plus que les opérateurs d'être exposés à des rayonnements supérieurs au niveau de 5 mSv et que les doses de neutrons étaient presque les mêmes que les doses de rayonnements gamma. Les opérateurs ont reçu environ 75 % de leur dose pendant qu'ils portaient ou transportaient la jauge. La dose aux mains est semblable à la dose au tronc, tandis que la dose aux pieds est de 6 à 30 fois plus élevée. Les rayonnements gamma sont la principale source de rayonnement qui contribue à la dose que reçoivent les opérateurs.

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SUMMARY

In Canada, there are now over 450 licensed organizations using portable moisture-density gauges. They reside mainly in the engineering-consulting services industry and in large quality assurance groups within government organizations. Most of these groups maintain inventories of several to many tens of gauges, and often have staff dedicated full-time to their use and maintenance.

Currently, regulations do not require routine wearing of radiation dosimeters, nor are operators required to be Atomic Radiation Workers as defined in the Atomic Energy Control Act. However, it is recognized that the available dose-related data are limited and the potential does exist for a significant dose accumulation among users. Dose accumulation may arise from improper use, malfunctioning equipment, maintenance and repair operations, transportation of the gauge, or simply by repeated operation over extended periods.

Field studies were conducted in several regions of Canada to measure actual radiation exposures of operators using commercial moisture-density gauges under different situations. Newly developed dosimeter technology (bubble detectors) and conventional dosimetry techniques (thermoluminescent dosimeters (TLDs), integrating electronic dosimeters (DRDs), and CR-39 neutron track-etch detectors) were used to identify the doses to 23 moisture-density gauge operators and maintenance staff. Most of the passive dosimetry was supported by conducting radiation field mapping and time accounting whenever a moisture-density gauge operator handled or was near a gauge.

Radiation doses to the body and extremities during a typical day's work were generally below the TLD, DRD, and CR-39 detection thresholds of 10 to 30 μ Sv. Of the 19 individuals monitored (17 operators, 2 maintenance workers) with these methods, only two showed any measurable dose to the body and/or extremities. One was a small neutron exposure received while conducting a lengthy repair to a gauge; the second was a gamma and neutron exposure to an operator using a gauge for soil compaction in a trench environment. In both cases, registered doses were very near the detector thresholds. Because of the limited precision and sensitivity available with the TLDs, DRDs, and CR-39 at low dose rates and low integrated doses, radiation field mapping and time accounting proved more useful in establishing dose levels for gauge operators. Radiation doses measured using survey methods provided a useful estimate of total dose to the body and provided some indication of the operations and activities most likely to contribute to dose. Radiation doses were recorded during gauge transport to and from a work site in vehicles (28%), while carrying the gauge between measurement locations (45%), and during site preparation and measurement operations (27%). Daily maintenance and cleaning contributed very little to accumulated radiation doses among operators. The geometric mean for the total single-day gamma dose to the human trunk (17 operators) was 2.2 μ Gy.

Newly developed bubble detectors were used throughout the study. Initially they were used to measure neutron exposures for all participants. During the latter stages of the program, new gamma radiation bubble detectors were incorporated to provide information on the spacial distribution of the dose to the operators.

Detectors placed at the wrist and ankle locations of three operators indicated that the gamma radiation dose to the hands was very nearly equal to that experienced at the trunk, but the dose to the feet area was 6 to 30 times higher. The depth of a measurement and the operating configuration of the instrument has a great influence on these doses.

The use of neutron and gamma bubble dosimeters among maintenance and repair workers indicated that neutron and gamma doses were roughly the same. The dose to the hands was also about the same as that to the trunk, which would be approximately 5 mSv after about 200 hours of actual hands-on bench top repairs. This contrasts with a field scenario, where there is relatively little likelihood of gauge operators exceeding the current regulatory dose limits for members of the public.

Moisture-density gauges are useful quality assurance devices in the construction industry. Doses to operators (from both gamma radiation and neutron radiation) are low. The greatest reduction in dose can be achieved by minimizing the length of time a gauge is carried and by storing gauges as far away as possible from vehicle occupants during transport.

Maintenance personnel can reduce their exposure by reducing the time spent in close proximity to moisture gauges. This is so even with the source rod removed, as a neutron hazard is still present and can contribute significantly to dose.

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1. Introduction

1.1 Background and Objectives

Radiation-based measurement techniques are used in a variety of disciplines in research, agriculture, and many of the manufacturing and industrial sectors. One of the major commercial applications of these techniques which has evolved during the past 25 years is the use of gamma attenuation and neutron moderation to measure bulk densities and moisture in soil and hydrogenous material. A large range of nuclear-based moisture-density gauges has been developed to service these measurement needs, and virtually any civil engineering quality assurance program for projects undertaken in Canada incorporates the use of portable nuclear gauges.

In Canada, there are now over 450 licensed organizations using portable moisture-density gauges. They reside mainly in the engineering-consulting services industry and in large quality assurance groups within government organizations. Most of these groups maintain inventories of several to many tens of gauges, and often have staff dedicated full-time to their use and maintenance.

By design, the hazards resulting from radiations emitted by the gauges are relatively small. Weak sources of fast neutrons (≈ 1600 MBq $^{241}\text{Am-Be}$) are not particularly hazardous unless their containment is breached or they are removed from the unit. Gamma radiation from ^{137}Cs (≈ 400 MBq) is well shielded, either from within the units or by the materials which are actually being monitored during gauge operation. Estimates of the radiation doses likely to be accrued by gauge operators have been theoretically determined by the manufacturers⁽¹⁾, and through early studies⁽²⁾ of moisture-density gauge hazards conducted on some of the first-generation instruments. This information has been augmented by the periodic radiation monitoring of the users with thermoluminescent dosimeters (TLDs). Together these methodologies have led to the conclusion that the total annual radiation dose to operators is likely well below the 5 mSv limit allowed members of the general public.

Currently, regulations do not require routine wearing of radiation dosimeters, nor are operators required to be Atomic Radiation Workers as defined in the Atomic Energy Control Act⁽³⁾. However, it is recognized that the available dose-related data are limited and the potential does exist for a significant dose accumulation among users. Dose accumulation may arise from improper use, malfunctioning equipment, maintenance and repair operations, transportation of the gauge, or simply by repeated operation over extended periods.

This report summarizes a study conducted for the Atomic Energy Control Board (AECB) of Canada. The study examined the hazards associated with the use and operation of several commercial moisture-density gauges, and obtained data on the exposures received by operators of the gauges under a variety of field situations. Underlying these specific objectives is the need to evaluate the impact of using a 1 mSv annual dose limit for members of the general public as suggested in the recently issued AECB consultative document C-83⁽⁴⁾.

1.2 Approach and Methodology

The study program focused on two main items. First, a comparative examination of the radiological hazards of gauges commonly used in Canada was undertaken. Evaluations were based on design features and manufacturers' recommended operating procedures. Secondly, a series of field studies was performed to examine all aspects of gauge use. Radiation doses received by gauge operators were monitored by both passive and active dosimetry in a variety of situations involving actual field measurements, gauge cleaning, and gauge maintenance. Voluntary test subjects for the field work were provided by a number of organizations; all were involved in the civil engineering field. Because most gauge use is associated with the construction industry (highways, large buildings, airport runways, etc.), it was felt that measurements of dose in these applications were likely to yield comprehensive data on the general level of exposure of the most exposed population groups.

Gauges selected for inclusion in the study were manufactured by Troxler Electronics Laboratories Inc., North Carolina, Campbell Pacific Nuclear Corporation, Pacheco California, and Humboldt Scientific Inc., Raleigh, North Carolina. Other moisture-density gauges are used in Canada; however, the vast majority of routine and frequent usages are associated with instruments of the above-noted manufacturers. All gauges utilized in the study were owned and operated by the various participating organizations.

2. Moisture-Density Gauges

2.1 Theory of Operation

The mechanical properties of construction materials (soils, soil aggregates, concrete, asphalt), such as deformability, reaction to compression and sheer stresses, and plasticity, can be related to three general parameters: grain size, density, and water content. Nuclear-based moisture-density gauges provide a simple non-destructive method for estimating bulk densities and moisture content in commonly used construction materials, thereby providing data necessary to estimate the stability of the construction materials. Because measurements can be made in-situ, nuclear-based moisture-density gauges have become the predominant means for quality assurance testing at work sites. A material's make-up is determined by comparing the interaction of radiation in the unknown material with the radiation interaction in standards of known composition, density, and hydrogen content.

Moisture-density gauges consist of several elements: radiation sources (an ^{241}Am -Be neutron source and a ^{137}Cs medium-energy gamma source), detectors for both neutrons and gamma radiation, a shielding and housing package and an electronics package comprised of at least one scaler. Figure 1 depicts a generalized arrangement of the instrument. The gamma source is fixed at the end of a movable rod which is shielded when retracted into the instrument housing. The neutron source is fixed on the bottom base plate of the unit within the housing of the moisture-density gauge.

Density measurements are taken in either of two configurations:

1) In the direct-transmission mode, the source probe containing the ^{137}Cs is extended into the ground or medium through a preformed access hole. The attenuation of the direct gamma radiation is related to the material density by the following equation.

(1)

$$I = I_0 e^{-(\mu/\rho)\rho x}$$

where: x = thickness of the material
 μ/ρ = mass attenuation coefficient
 ρ = density

In practice, equation (1) is modified to take into account source-to-detector geometry, typical mass attenuation coefficients for construction materials and soils, detector efficiency, and calibration factors. A response function is then generated, relating the observed count rate at the detector with the average density of the material between the source and detector. For most materials, once a count rate is determined, operators of the gauges need only refer to the count rate to establish densities.

A typical response function for direct transmission-mode operation (Figure 2) is given in Figure 3.

2) In the backscatter mode, the source is simply extended from the housing to near the surface of the ground or medium. The emitted gamma radiation is attenuated and Compton-scattered by the material below the source. Some of the radiation is scattered back to the surface, to the detector in the gauge. Because the Compton-backscatter is related to the electron density of the scattering media, material density can be inferred. The interaction process still follows the generalized form of equation (1); however, the modifying parameters are different. Instrument configuration is given in Figure 4. The relationship of count rate to density in the backscatter mode is given in Figure 5.

Moisture content measurements are made exclusively in the backscatter mode with the type of instrumentation utilized in this study. Fast neutrons from the ^{241}Am -Be source located in the detector housing are slowed down and thermalized by the hydrogen nuclei in the unknown media. Some of these neutrons are scattered back to the gauge and detected by thermal neutron detectors. The number of thermalized neutrons so detected is directly proportional to the hydrogen contained in the monitored media; consequently, moisture or hydrogen content can be inferred. Response functions for moisture content are far more complex than gamma attenuation response functions and require careful selection of the source-to-detector distance to achieve a reasonable effective depth of measurement.

Some early models of moisture-density gauges contained only a single ^{226}Ra -Be source located in a source rod, for a combination surface and depth gauge, or else they were located completely within the unit housing for operation in the backscatter mode only. The ^{226}Ra provided both the photons necessary for density measurements, and the alpha particles which interact with the beryllium to create a fast neutron source.

Though moisture and density evaluations of common construction materials are based on complex interactions of radiation with matter, commercial manufacturers have simplified the measurement considerably. Operators need only position the unit in the appropriate location and configuration and relate the observed count rate in the various detectors to the appropriate density or moisture content. Some newer instruments have the required response functions and computation algorithms in small microprocessors, enabling such devices to give direct readouts of moisture and density.

2.2 Radiation Hazards

Essentially, only external radiation hazards are present with the use and maintenance of moisture-density gauges. The potential for contamination hazards does exist, as with all discrete radioactive sources, but generally only as a consequence of containment failure. Containment failure is considered unlikely to occur unless the equipment has been involved in an accident. Review of source encapsulation integrity is beyond the scope of the present work.

Figure 6 illustrates the radiation fields which would be created by sources typically found in moisture-density gauges if unshielded. Evidently the gamma radiation sources pose the most significant hazard. For common-source strengths of ^{137}Cs , whole body exposure 1 m from an unshielded source for 1500 hours would result in an accumulated dose equivalent equal to the annual limit of 50 mSv allowed Atomic Radiation Workers. The limit established for members of the general public would be reached with only a 150-hour exposure. Though shielding in moisture-density gauges reduces the radiation fields by a factor of 50 or more, some aspects of gauge use and maintenance necessitate removing the source from its shielding. Operating the gauge in the direct-transmission mode is an example of such use. The soil or medium being monitored then provides the shielding. During gauge maintenance the ^{137}Cs may have to be removed completely from the unit, or some of the shielding may have to be removed to implement repairs. Referring to Figure 6 and the shielded dose-equivalent rates outlined in Table 1, it is apparent that operators may be exposed to a very wide range of gamma dose rates, depending on how the gauge is being used. The range of neutron dose rates is smaller in both magnitude and range; nevertheless, neutrons can still contribute to operator dose.

Design of the instruments, operating procedures, and maintenance procedures is intended to keep accumulated doses low with respect to the relevant dose limits. For example, manufacturers' estimates of accumulated dose-equivalents while operating the gauges more-or-less on a full-time basis, are between 30 μSv and 50 μSv per week of operation. Individual dose will, of course, depend on the extent of involvement with the gauge. One would expect that individuals involved solely in field use would accumulate lower annual doses than those involved in gauge maintenance.

Listed below are factors and use aspects that can influence user/operator exposure. In the discussion that follows the list, each factor is examined within the context of: the instrumentation commonly used in Canada, its recommended operating procedures, and observations made during the field studies under actual-use conditions. The parameters are:

- 1) gauge design and packaging
- 2) gauge storage
- 3) transportation
- 4) maintenance and repair
- 5) operating procedures
- 6) field environments

2.3 Gauge Use and Operation

2.3.1 Design

Detailed specifications for several models of gauges are summarized in Table 1. Source strengths for each device are nearly the same (within 20%). A comparison of the radiation dose-equivalent rates at the surface and 1 m for some models manufactured by Troxler, Humboldt and Campbell Pacific are given in Table 2. With the exception of the Campbell Pacific data, all values were derived from the standard operating manuals. It should be noted that there are some variations in source strength among identical models. Where comparative values for the Campbell Pacific units were needed, dose-equivalent rates were estimated with an AEP 5302 survey meter during the field studies. Considering the accuracy of making dose-rate measurements with portable instrumentation (manufacturer data was also derived from measurements with portable instrumentation), and the potential differences in source-to-detector geometry with surface or contact measurements, no difference is apparent in the radiation fields produced by the Troxler, Humboldt and Campbell Pacific gauges. In terms of operator dose, simply being in the vicinity of a gauge with the source retracted into the "safe" position would result in the same dose for each model noted.

2.3.2 Transportation and Packaging

Manufacturers' recommendations and license requirements require that the gauge be transported in an appropriate transport case. Manufacturers supply these containers with the instrumentation. Shipping packages qualify as Type A packages with a transportation index of 0.1.

A user of a moisture-density gauge is generally concerned with two aspects of transporting the gauge, namely: 1) moving the gauge between measurement areas within a large site, and 2) moving the gauge to and from work sites. Any dose incurred as a result of transporting the gauge is influenced by the mode of transportation and the physical dimensions and characteristics of the gauge packaging. Generally, the larger the packaging the more limits imposed at positioning a gauge in unoccupied parts of a vehicle.

Most units of early manufacture came with a single case for both the gauge and accessories. These cases qualified as type A shipping packages. These also tended to be bulky and heavy when fully equipped. In fact, they are difficult to locate in unoccupied parts of compact automobiles; this may encourage the

practise of removing the gauge from the container for transportation to a work site. If the gauge is placed closer to occupied areas of a vehicle, more dose could be accumulated by occupants. Alternatively, large cases ensure that the proximity to a gauge is restricted, thus limiting the dose.

Most gauges of recent manufacture have smaller packaging or utilize alternate multiple packages for moving the gauges from work site to work site. As with single large units there are advantages and disadvantages. Higher dose rates are present on the container surfaces; however, the greater flexibility afforded in storing the gauge in a vehicle probably outweighs the disadvantage of the higher dose rates. The higher dose rates are of concern only if the package is placed near the operator during transport, and then only if an operator spends considerable time transporting the gauge.

One aspect of gauge design, packaging design, and gauge transportation which does influence operator dose occurs during winter use of portable moisture-density gauges. To achieve low power consumption, all moisture-density gauges utilize liquid crystal displays. These can operate only within a limited temperature range, usually to -10°C . However, Canadian winters in some areas typically have temperatures well below -10°C . Consequently, if an operator hopes to use a gauge in these circumstances, the gauge must be placed in a heated environment during transportation. In small trucks, generally the only option is to place the gauge in the occupied area of the cab. Dose rates approaching $10\ \mu\text{Sv/h}$ could be present under these situations at the driver's position.

2.3.3 Maintenance and Repair

An individual's closest proximity to a moisture-density gauge occurs during maintenance and repair operations. Some may be done by an operator who has received appropriate training while others must be performed by qualified service technicians. Table 3 lists the type of activities which must be performed, as well as dose rates which may be encountered during these situations. Essentially, the hazards posed by the gauges during these activities are the same, irrespective of the manufacturer.

2.3.4 Operating Procedures

From the perspective of gauge operation and operator exposure to radiation, very little difference in radiation hazard exists among the various gauges. The potential for exposure is partly related to the functional processing capabilities of the instrument as well as the amount of time an individual must spend handling the gauge in order to obtain the required information.

2.3.4.1 Gauge Standardization

Use of a moisture-density gauge requires that it be standardized to validate its operation and to take into account variations in natural background. This is normally done at the work site. The moisture-density gauge is placed on a reference standard with the source in the fully retracted storage position. Then the appropriate procedures (depending on the model) are followed to obtain the reference counts. Operators are exposed during the gauge set-up and operation of the front panel controls. As indicated earlier, radiation fields are

essentially the same for instruments manufactured by Troxler, Campbell Pacific and Humboldt. However, there are differences in the time necessary to operate the front panels. These time differences exist within instruments of the same manufacture and are dependent on the microprocessing capability of the device. Because of the computational capabilities and the range of information which can be obtained with the microprocessor-based units, more time is sometimes required to operate at the front panel. For example, the time required to kneel in front of a manual moisture-density gauge is only about 10 seconds. For a microprocessor-based unit this time can approach one minute. Due to the frequency of standardization requirements, functional capabilities of the instrument will have a negligible impact on operator dose.

2.3.4.2 Site Preparation

Preparation of the site for a measurement depends on whether measurements are to be made in the backscatter or direct-transmission modes and also on the material which is to be monitored, i.e., soil, gravel, concrete, and asphalt. If the manufacturer's recommendations are followed by keeping the gauge several metres away during initial site preparation, no appreciable exposure will result. Seating the gauge is a function of measurement requirements and the doses are relatively independent of gauge design. Gauges with smaller seating areas may be faster to seat on problem surfaces with many surface irregularities; however, this is generally associated only with measurements made in the backscatter mode. Proper attention to initial site preparation, before placing the gauge at the measurement location, would minimize any radiation exposure.

2.3.4.3 Operation and Measurements

All operations of moisture-density gauges require the release of a source-rod trigger mechanism which opens a shielding shutter at the base of the gauge and unlocks the source-rod, permitting its extension out of the shielding. In the case of density backscatter measurements, the source is only partially withdrawn from the shielding. Of the manufacturer's recommendations, only one procedure can directly effect different operator doses. This occurs when the operator lowers the source rod into the access hole in the direct-transmission mode. Two procedures are recommended in the various manufacturers' literature: 1) the gauge is tipped backwards, raising the end of the unit with the ^{137}Cs source rod. The release mechanism is activated and the source is extended four or more inches. Then the operator lowers the moisture-density gauge, directing the end of the source into the access hole. The device is seated and the source rod is positioned at the required depth. 2) The second method involves scribing the soil surface around a template which is used to form the access hole, and positioning the gauge carefully within the scribe markings. The source rod is then lowered to the measurement depth.

For some measurements made in hard materials like cured concrete (which have had access holes formed at the time of pouring), the first method is the only easy means of positioning the source.

The first method poses some obvious disadvantages. Assuming that the source is unshielded for 3 or 4 seconds before the unit is repositioned on the ground and that the operator's body is within 60 cm of the source, dose rates can be of the order of 1000 μ Sv/h. In the second method, with the gauge having to be placed inside scribed marking and seated before the source is extended, the operator is subjected to dose rates of only about 50 μ Sv/h. An operator could spend up to 3 minutes placing a gauge within scribe marks and lowering the source-rod, and thereby accumulate the dose the user of method 1 would receive in only a few seconds. From purely radiation protection considerations, the first method should be avoided whenever possible.

Radiation exposure, while making measurements on the construction media, is essentially the same as when using the reference standard. There may be a higher level of operator dose associated with instruments utilizing microprocessors if the full range of functions is used. With manual instruments, computations of compaction using the density and moisture results can be done in an area well-removed from the moisture-density gauge, thus lowering overall operator dose. The depth of measurement has the most important impact on operator dose.

3. Radiation Exposure Field Studies

3.1 General

The purpose of the field program was to quantitatively determine the radiation exposures arising from the use and maintenance of portable moisture-density gauges in Canada. The design of the experimental program was influenced by the requirement that sufficient estimates of operator-equivalent dose equivalent data be obtained to allow the subsequent estimation of accumulated dose to the average moisture-density gauge user. This required field measurements over as large a geographic area as possible in order to accommodate possible variations in use and measurement applications. The large area also provided an indirect means of making the measurements under varying geological conditions.*

The design of the actual monitoring program was influenced by the requirement that whole body and extremity doses to operators be estimated for the different aspects of gauge use and maintenance - specifically:

- 1) transportation
- 2) set-up
- 3) operation
- 4) maintenance and cleaning

* Geological conditions were considered to be unimportant because most moisture-density gauge uses were made on either man-made materials such as concrete and asphalt, or on materials whose general composition was controlled, such as graded gravels or granular fill.

Added to these requirements was the need to identify the dose equivalents received per measurement.

In order to meet these objectives, a dosimetry program was devised incorporating both active means and passive means. Active dosimetry consisted of mapping the radiation fields in the vicinity of the gauge operator and estimating the time spent by the gauge operator within the radiation fields. This technique was limited to gamma radiation and was performed for each aspect of gauge use. Passive dosimetry consisted of fixing various types of dosimeters to the operator's trunk and extremities (Figure 7). It was anticipated at the outset of the program that the standard passive dosimeters would be operating very near their respective minimum detectable levels.

Four field-study programs were performed as noted below:

Central Canada Study

- 9 moisture-density gauge operators were monitored under conditions of normal field operations
- 1 maintenance technician was monitored during a cleaning operation.

Western Canada Study

- 8 moisture-density gauge operators were monitored under conditions of normal field operations
- 1 maintenance technician was monitored during a moisture-density gauge maintenance and repair

Maintenance Study

- 1 maintenance technician was monitored on two separate occasions during a series of maintenance operations involving 4 moisture density gauges

Quebec/Special Study

- 3 moisture-density gauge operators were monitored during field use of the gauges using newly developed experimental gamma-radiation bubble detectors.

3.2 Methods

3.2.1 Gamma Dosimetry

Gamma dose rates were measured at the moisture-density gauge operator's location with a calibrated AEP 5302 background survey meter. The instrument had an effective range of 0.001 $\mu\text{Gy/h}$ to 20 $\mu\text{Gy/h}$ and was operated with a time constant of 4 seconds. Depending on the particular work environment, the radiation fields were recorded at near-ground level, knee height, and waist level during periods of gauge use. During transport of the moisture-density gauge,

radiation fields were measured predominantly at the back upright of the vehicle seat occupied by the gauge operator. Additional radiation measurements were made as necessary. Passive gamma radiation dosimetry was accomplished by using calibrated electronic recording dosimeters and a specially-calibrated set of thermoluminescent dosimeters. The electronic dosimeters were AEP 5237 Alarming Dosimeters with a detector limit of $10 \pm 5 \mu\text{Sv}$. The TLDs were of the type usually used in environmental monitoring and utilized a special set of controls which were kept with the TLDs except during periods when the measurement TLDs were used. The estimated uncertainty of the subsequent readings was $\pm 37 \mu\text{Sv}$.

3.2.2 Neutron Dosimetry

All neutron dosimetry for extremity dose used CR-39 track-etch detectors. Whole body dosimetry was performed with CR-39 track-etch detectors and an experimental neutron bubble detector (BD-100). The bubble detector had a lower limit of detection of approximately $2 \mu\text{Sv}$. Through the utilization of controls the lower limit of detection for the CR-39 neutron detectors was $30 \mu\text{Sv}$ for fast neutrons and $5 \mu\text{Sv}$ for thermal neutrons. Uncertainty was $\pm 30 \mu\text{Sv}$ and $5 \mu\text{Sv}$ respectively.

3.2.3 Special Dosimetry

During the maintenance field study and the Quebec study, special experimental dosimetry was used in an effort to improve the sensitivity of the passive dosimetry measurements. Newly developed gamma bubble detectors manufactured by the Bubble Technology Unit at the Chalk River Nuclear Laboratories provide sensitivities under some operating circumstances below $1 \mu\text{Sv}$. The use of these detectors vastly improved the sensitivity and accuracy compared to previously used dosimetry techniques. Neutron bubble detectors (BD-100) were used in conjunction with the gamma bubble detectors for both whole body and extremity dose estimates. Some restrictions are associated with the use of these experimental dosimeters, particularly in the area of temperature compensation.

3.2.4 Data Presentation

All data are presented in units appropriate to the calibration of the equipment or dosimeters used to make the measurement. In order to preserve information on how a particular measurement was determined, no attempt has been made to normalize to a common set of units. From the practical viewpoint, little is lost making a direct comparison between results reported in grays and those reported in sieverts because the uncertainty in the results is larger than any conversion correction.

4. Results

4.1 Central Canada Field Study

4.1.1 Applications and Operator Activities

Moisture-density gauge field operations were monitored in four geographic areas: Toronto, Hamilton, North Bay, and Round Lake Centre. Operators participating in the measurement program worked for one of three different organizations, each of which had extensive moisture-density gauge programs. Three gauge operators were provided by each organization. Documentation to support

the operator training was based on manufacturers' manuals for two of the participating companies, while the third utilized an in-house developed manual. All equally identified the specific hazards associated with the gauge use.

Table 4 provides a synopsis of operator activities and the specific measurement applications. Almost all gauge-use dealt with compaction of construction graded gravels, typically referred to as granular A or B. Some measurements were made on local soils over which the graded construction materials would later be applied. Soil and material descriptions were those provided by the gauge operators. Two operators, G and H, in addition to making compaction determinations of gravel, monitored compaction of asphalt. Operator G performed a single measurement operation on old asphalt as a demonstration. Operator H did the asphalt measurements as part of the site work requirements. All asphalt measurements were made in the backscatter mode with the source-rod only slightly extended from the gauge shielding. Three operators worked in each of the Toronto and Hamilton areas. For each of the other geographic areas, one operator was monitored.

4.1.2 Direct Gamma Surveys

Estimates of operator dose by the direct survey methods were made from the time the operator set up to make the first use of a moisture-density gauge, normally a calibration, until all gauge operations were concluded. Specifically, the operations covered were gauge set-up and site preparation, placement of the gauge at the measurement location, activating/deactivating the counting circuits, moving the gauge from one measurement location to another, and simply being in the vicinity of the gauge. Gamma dose rates were measured at approximately waist level. Logistics of recording and measuring time and dose rates for the extremities were virtually impossible.

A summary of individual operator radiation dose estimates appears in Table 5. Each dose estimate is categorized by operator, material type, and gauge configuration. Data in Table 5 represent only those periods when the operators prepared the measurement site, positioned the gauge and source-rod and were present in the vicinity of the gauge during the measurements.

Normalized dose estimates per gauge measurement averaged 60 nGy. Only operator G's dose departed significantly from the mean. His dose per unit measurement was two to three times the dose associated with the other operators. There are several reasons for his higher dose. Operator G's work area was in a pipe trench which was being backfilled with granular B gravel. The trench was compacted in a series of lifts and once the compaction of the lifts was judged to be satisfactory (by gauge measurement), more backfill was added and compacted. Initially the trench was 1.5 m in depth. The depth was subsequently reduced to less than 60 cm at the completion of the work. Because of trench geometry, scattered radiation is higher. This is common and manufacturers suggest that calibrations with the reference standard be done in trench environments to correct for higher radiation levels. In addition to the higher radiation levels in the vicinity of the gauge, the physical geometry and backfill material made set-up operations longer. The orientation of the gauge at the base of the trench required that operator G stand to the side of the gauge, where the

radiation levels tended to be twice as high compared to similar distances in front of the gauge. Radiation fields were still low, being less than 1 $\mu\text{Gy}/\text{hour}$.

Carrying moisture-density gauges between measurements, and transporting the gauge by vehicle at both the construction site and to and from the work sites, also contributed to operator dose. Doses arising from these situations are very operator-dependent, unlike the doses which arise during use. Table 6 presents dose estimates to field operators A to J. The hand-carried dose was approximately that of the waist and lower trunk, and was basically determined from the time the operator carried the gauge. Because of the weight of the gauges, operators generally did not carry the gauges for extended periods. Gamma dose rates were typically of the order of 500 to 1000 nGy/h or less, at waist level. Transportation dose was a function of the time spent in a vehicle with the gauge located in the vehicle.

Gamma dose rates inside vehicles ranged from a high of 1.4 $\mu\text{Gy}/\text{h}$ when the gauge was located in the front cab of a pick-up truck, to near-background levels when placed near the rear doors of a full-sized van.

Table 7 summarizes the estimated operator gamma radiation dose due to gauge operation in the Central Canada field study as determined by the direct survey methods.

The average gamma dose per gauge operation, including hand-carrying, is approximately double the average derived from the basic operation of the gauge (130 $\text{nGy}/\text{measurement}$ vs 60 $\text{nGy}/\text{measurement}$). The scatter in the data is also larger. Total estimated gamma dose for all aspects of gauge-use generally indicate gamma doses less than 10 μSv . The average gamma dose estimates for all operators in the Central Canada study was approximately 3 μSv per operator.

4.1.3 Passive Dosimetry Results

TLD, CR-39, and DRD dosimetry results for the extremities are given in Table 8. Most values were below the lower limit of detection, with the exception of operators C, E, F, G, whose direct-reading dosimeters indicated some exposure. These operators also had the highest accumulated gamma dose estimates from the direct-survey portion of the study. Operator E was the only operator to register a whole body gamma dose in excess of 10 μSv . He also had the highest whole body estimated dose of 8.3 μGy . Operator C received some extremity exposure to his right hand, according to the direct reading dosimetry results. The fact that the exposure occurred on the right side of the body is consistent with the fact that he transported the gauge on the right passenger side of the cab of a half-ton truck, and carried the gauge in his right hand.

Operator G's DRD results appear to indicate that he received the highest dose; however, the dosimeters used retain the counts in an internal counter which, when full, is equivalent to 10 μSv . This counter, however, is not cleared when the DRD is reset; consequently some residual counts remain, which results in an average error of $\pm 5 \mu\text{Sv}$ - but can be as large as nearly 10 μSv . If the doses

recorded by the DRD's are high by 5 to 10 μSv , the results are in good agreement with the TLD results, which indicate that the highest exposure occurs to the feet.

CR-39 neutron dosimetry results were all below detection limits; however, some neutron dose was recorded by the neutron bubble detectors placed at the trunk location. Those operators indicating a neutron exposure were operators G and E, which is consistent with the other results, as operators G and E were the highest-exposed operators.

The neutron doses estimated for the operators E and G were (5.5 bubbles/10 μSv at 22°C) 5 μSv and 14 μSv . These results appear to be inconsistent with the gamma dosimetry results where operator G's gamma dose should have been lower than operator E's by a factor of two. There are, however, several aspects of both the gauge-type work conditions and operator activity which account for the neutron dose anomaly.

First, both operators used the same type of moisture-density gauges but the ^{137}Cs sources were different. Though both had approximately 1600 MBq of $^{241}\text{Am-Be}$, the ratio of ^{137}Cs activities was 6.2 to 8. Consequently, for the same gamma radiation dose, operator G would be expected to have close to a 25% higher neutron dose. Operator G's workplace was in a trench and, during the measurements, backscattered neutrons emitted from the walls of the trench may have served to alter the neutron to gamma dose rates in the trench. Indeed, increased neutron scattering would be expected. Another factor concerns the temperature dependence of the bubble detectors. In reviewing this concern two things must be kept in mind. Operator G's physical activities were more strenuous in preparing the site for the measurement and he typically needed twice the amount of time to prepare the measurement site.

The increased physical activity increases the heat output of the body, possibly raising the temperature of the bubble detectors worn on the body. This can change the response of the detectors in such a manner that neutron doses are overestimated unless careful tracking of dosimeter temperature is maintained. For example, the BD-100 detectors used in the Central Canada portion of the study had a 50% change in response in the temperature range 20°C to 30°C. Any of these temperatures can be achieved during use. Operator G's neutron bubble detector indicated the highest neutron dose of about 14 μSv , but even considering the possibilities of bubble detector over response, operator G received a more significant neutron dose than other gauge operators, as a result of using the gauge in a trench environment.

4.2 Western Canada Study

4.2.1 Applications and Operator Activities

As with the Central Canada study, three organizations participated by providing three gauge operators/maintainers. Operator training was also based on manufacturers' instrument manuals for six of the individual participants, and an in-house manual on nuclear-based measurements was used by the third group. All field monitoring took place in the Calgary and Edmonton areas.

Dose estimates were made under the conditions outlined in Table 9. Some of the applications were considerably different from those encountered during the Central Canada portion of the program. Backscatter density measurements were more frequently used, and concrete curbs and jersey barriers were examined in some road construction quality assurance programs. In addition, some of the operators routinely used asphalt gauges designed to test asphalt mixes before laying them. Because these devices employ fast neutron sources of about 10 GBq, there was a potential for additional neutron dose to the operators. Operator O actually used the asphalt gauge for a one-hour period during the work day and, because of the possible contribution to dose, passive dosimeter monitoring was continued. One aspect of the operator activities which may influence the dose estimates was the fact that one gauge operator experienced electronic problems with the gauge but performed a simulation of gauge use. Simulation of moisture-density gauge use also was done by operator R. In both these situations the gauge results obtained were not recorded or used; consequently, the operators spent less time in the vicinity of the instrument than they normally would.

Measurement depths used by several operators were 30 cm in the direct transmission mode. Very low gamma dose-rates are observed in the vicinity of a gauge in these circumstances. Operation at deep depths does not affect neutron exposure. Therefore, the ratio of neutron dose to gamma dose can be different depending on the measurement depth, because the Am-Be source is located in the instrument housing.

4.2.2 Dose Estimates from Gamma Surveys

Survey methods were identical to those done in the Central Canada study. The estimated doses for operators K through S are given in Table 10. A considerable range is observed, from a low of 30 nGy to a high of 1790 nGy. Operator N, who received the lowest, went through operation simulation and effectively turned the unit on (operation in backscatter mode), went away from the gauge vicinity and then returned. He would then put the source in the storage position, pick up the gauge and carry it a short distance to the next location, put it down and activate the unit for another measurement. The mean dose per measurement for all operators was 33 nGy. This is approximately half the value observed during the Central Canada study. This may be, in part, due to the fact that some of the gauge operations were simulations and the full exposure potential was not realized. Also, measurements made in the backscatter mode require less time in site preparation and, in some cases, the time spent near the gauge is negligible, contributing little to operator dose. Depth of measurements in the direct-transmission mode were generally deeper than in many of the Central Canada applications.

One piece of data was excluded from the data base used to produce the Table 10 summary. Operator R demonstrated the use of a moisture-density gauge application of a concrete jersey barrier, which is often used as a median for opposing lanes in highway construction. Because of the narrow width and general geometry, high radiation measurements were observed in the vicinity of the operator [Figure 8]. Operator R actually received an estimated dose of 400 nGy from the single measurement. Because these measurements are not made on a routine basis and are made only in the geographic area where operator R worked, the 400 nGy dose was excluded from the data summary.

Dose accumulations arising from carrying the gauges from one measurement location to another often contributed more dose to operators than actual gauge use. Table 11 illustrates this fact. For example, operators N and P received very little dose during operations but accumulated on the order of 10 times the operation dose while carrying the gauges.

Similar observations are apparent from the transportation data. Only operator N did not receive any dose in this category, largely because he performed the gauge simulations near the field office at the construction site.

Table 12 summarizes all gamma doses obtained by radiation time mapping. The highest was received by operator R, mainly due to gauge transport.

4.2.3 Passive Dosimetry Results

TLD, CR-39, and DRD results are presented in Table 13. Several results are considerably higher than similar measurements made in the Central Canada study even though the direct survey results would indicate that lower results should be expected.

Dosimeter responses above detectable levels were observed in all operators with the exception of operator P. Neutron doses were observed for three of the operators (K,S,O) where no other dose was recorded.

Operator K received a dose of 5 μ Sv thermal neutron to the right foot, which is at the detection level. One possible cause may have been the calibration process. Calibration requires placing the gauge on the reference standard which is placed on one end of the shipping case. This process effectively exposes the bottom of the gauge, which tends to have a higher neutron exposure rate than other surfaces of the gauge. In this situation only the operator's legs would be subjected to the higher dose rate. Gamma dose rates should be approximately the same but the lowest detectable gamma dose was 10 μ Sv.

Operators S and O also received neutron doses with no other dose identified. Operator O's CR-39 dosimeters on the waist and left foot recorded 60 μ Sv doses. The uncertainty in these measurements was ± 30 μ Sv, with 30 μ Sv being the lower limit of detection. However, operator O did use the Troxler 2226 asphalt gauge at the onset of the work and may have received the neutron exposures from this instrument. Neutron surface doses measured on the instrument with a BD-100 bubble detector were 190 μ Sv/h. Bubble detectors were placed on the trunk and on the right wrist area during the use of the device (1 hour). Neutron doses of approximately 7 μ Sv and 20 μ Sv, respectively, were recorded.

Relatively high neutron dose-rates were recorded at waist level for operator O. The total neutron dose (thermal and fast) was 210 μ Sv. No bubble detector response was recorded. Design neutron dose-rates for the Troxler instrument used are well below any dose rate, during the times he was monitored, which could have caused such a dose. Because none of the other CR-39 dosimeters indicated any significant exposure to neutrons, the 210 μ Sv reading may be erroneous.

TLD results near the lower limit of detection were found on operator L's right foot dosimeter. This dose is supported by DRD observations. Other low doses registered by the TLD's were for operator R (10 μ Sv right foot). Operator R carried the moisture-density gauge for a considerable distance in his right hand, causing the higher dose to the right foot area.

The highest TLD results were found with operator Q's doses to the left hand and left foot. Had the dose been attributed to carrying the gauge, a higher dose would have been observed on the right hand and foot (the operator carried the gauge in his right hand); however, this was not the case. Because of the magnitude of the doses (200 μ Sv and 140 μ Sv), the only cause would be direct exposure to the source. This was possible because the operator fully extended the source rod to the measurement depth (normally 25 cm) before inserting the rod in the access hole. However, DRDs would have supported a higher exposure, but none registered above 10 μ Sv. The only conclusion which can be drawn from this data is that operator Q may have received a slightly higher dose to his left hand and foot, but the absolute value is uncertain.

With the exception of the two very high readings on one TLD and one CR-39 dosimeter, the passive-dosimetry results are in general agreement with the direct survey dose estimates.

4.3 Eastern Canada Study/Special Study

4.3.1 General

The Eastern Canada study became a program option and was conducted approximately one year after the first two studies in order to take advantage of some very sensitive passive-dosimetry techniques employing bubble detectors for neutrons and gamma radiation. The gamma bubble detectors were developed between the fall of 1986 and the summer of 1987. Prototypes were used during the moisture-density gauge maintenance field study (section 4.4) to test their applicability for low-dose gamma radiation measurements. These proved that improved sensitivities by an order of magnitude could be gained by using bubble detectors for field dose measurements. Considering the average dose for each moisture-density gauge operator during the Central and Western Canada studies, the use of the bubble detectors would provide integrated dose in the range probably experienced by operators of moisture-density gauges. In addition, they had the potential to more accurately establish the level of dose to the extremities, even though TLD, DRD, and CR-39 dosimetry indicated low dose.

Three operators were monitored during field use with five sets of packaged bubble detectors (BD-100 and BD-gamma) manufactured by the Bubble Detector Technology Unit at CRNL. The detectors had sensitivities of 5 bubbles/10 μ Sv and 1.7 bubbles/10 μ Sv respectively. Temperature sensitivities are given in Figures 9 and 10. Because of the sensitivity of the BD-gamma detectors to temperature, each packaged set was insulated to provide some means of controlling bubble detector temperature, and hence, sensitivity. The insulation also served to reduce the impact of body heat, keeping the dosimeters within a reasonable temperature range. The usable operating temperature range was considered to be between 23°C and 30°C. No auxiliary dosimetry means were used to establish the levels of radiation dose.

4.3.2 Applications and Operator Activities

Three operators were monitored in Montreal using staff from two organizations. One group had an established moisture-density gauge program with several operators working out of the same office, while the second group had moisture-density gauge operators working out of two regions. The measurement program was terminated with the third operator, largely because of the difficulties of controlling the temperature of the bubble detectors in outdoor environments.

Operator activities are noted in Table 14 and are, in general, similar to the types of activities moisture-density gauge operators were engaged in in other parts of the country. The instruments used were more automated versions of the other Troxler models. The Troxler 3411-B is essentially the same as the other instruments in the 3400 series. Radiation at the panel did appear to be less than the other Troxler 3400 series instruments.

4.3.3 Dose Measurements

No neutron doses were detected by the BD-100 bubble detectors. The results from the BD-Gamma detectors are listed, for each individual operator, in Tables 15, 16 and 17.

Temperature fluctuations observed with thermometer responses in the dosimeter sets were sufficient to change gamma detector responses from 0.03 bubbles/ μ Sv to up to 6 bubbles/ μ Sv at 30°C. Temperatures were checked routinely, but when frequent changes occurred, no effort was made to count the bubbles in the detector (possible to enhance fluctuations). Temperature variations occurred during physical work (increase) and transportation in a compact heated automobile (increase). When the operator completed travelling or frequent physical work, the temperature inside the dosimeter jackets would slowly decrease. Results listed in tables 15, 16, and 17 are for periods when temperatures were stable or when the temperatures and bubbles in the detectors were counted or checked frequently.

It was difficult to compute the total doses received by the operators with the bubble detectors because of missing data (values below detection limit) and the different detection limits. However, there were several sets of activities with a complete set of dose results for the extremities and trunk.

For each of the operators, the highest values observed were for the extremities on the side of the body used to carry the gauge, or the lower leg area. Data for operator T indicate much higher extremity dose (feet) compared to the whole body. This is expected because measurements were made in the direct transmission mode at relatively shallow depths (10 cm). Similar observations are apparent for operator U and, to a lesser extent, operator V.

A condensed summary of cumulative operator dose is given in Table 18. Average doses to the hands are approximately the same as the whole body dose but the dose to the feet ranges from 6 to 30 times the whole body dose. Shallow direct-transmission measurements increase the ratio of lower leg doses to trunk doses. For operators T and U, the mean doses per unit measurement (where complete data sets were obtainable) were 190 μ Sv (lower arms) 200 μ Sv (body) and 1000 μ Sv (lower leg). Insufficient data were obtained for operator V for a valid comparison with the other operators.

4.4 Maintenance

4.4.1 General

Apart from moisture-density gauge use and operation, maintenance also has the potential to expose operators. Data presented in this section of the report are a compilation of observations and measurements made during the three field studies on gauge usage and from a short study specifically examining maintenance doses. Measurements in the latter study were made with prototype BD-gamma bubble detectors.

During the field studies, gauge cleaning activities were observed being performed by moisture-density gauge operators E, F, G, and U*. Cleaning requirements were relatively infrequent and most operators cleaned the gauges when they noticed a degradation in the performance of the source-rod movement. Most organizations and operators reported that cleaning was performed 1-2 times per year per gauge. The need to clean the shutter area is greatly reduced if only backscatter measurements are made.

4.4.2 Doses from Maintenance

Table 19 gives a summary of individual operator activities when performing maintenance functions. Cleaning the shutter area typically required only 2-5 minutes (E, F, G). Operators spent only about half that time in the proximity of the gauge. Even with the shutter block removed, radiation fields away from the direct beam are the same as with the instrument in the 'safe' storage mode. Dose rates for typical instruments are given in Tables 2 and 5. From these data (and the time needed to perform a cleaning operation), the anticipated body dose (trunk area) should be about 0.3 μ Sv. Operator U was monitored with a BD-Gamma bubble detector (30°C sensitivity 0.1 μ Sv) and a dose to the body and extremities of 0.1 μ Sv and 0.2 μ Sv, respectively, was recorded.

Other instrument inspection, lubrication, and cleaning operations require the removal of the ^{137}Cs source-rod. This was done by operators D and M. Operator D worked with a Troxler manufactured moisture-density gauge and operator M used a Campbell Pacific gauge. There was no significant difference in the relative hazards present with the different gauge types. Only operator M was monitored with passive dosimetry methods.

Operator D spent about 30 minutes working with the moisture-density gauge, of which 5 minutes was used for source-rod removal and installation, and transfers to and from auxiliary lead shielding. Measured gamma doses to the body area during the procedure were: 1) source-rod removal/installation, 15 μ Gy/h; 2) source rod transfer, 200 μ Gy/h; 3) bench maintenance, 0.3 μ Gy/h. Overall gamma dose was estimated to be about 3 μ Sv - very similar to the doses received by operators for field use. Neutron doses were not measured. Annual doses would depend on the frequency of maintaining the gauges and on the neutron exposure.

* U did not actually do the work but the dosimeter packages were transferred to the individual who cleaned the gauge.

Operator M was engaged full time in the servicing of moisture-density gauges and other equipment used in quality assurance programs. Table 20 gives a summary of doses to the body and extremities observed while operator M performed maintenance and repair operations on a Campbell Pacific gauge. Repair activities lasted slightly more than one hour and the source-rod was removed from the unit during most of the work. Doses observed with the BD-100 and CR-39 detectors were in good agreement except for the CR-39 detector at the operator's waist location. The CR-39 value was quite low (detection level). The results, of the order of 20-50 μSv , are within the range of doses which can be expected from neutron exposure alone by working in close proximity to the moisture-density gauge.

Instruments repaired by operator M were estimated at 120 per year for moisture-density gauges during the construction season with off-season maintenance to 53 moisture-density gauges and 23 asphalt content gauges. Consequently, the potential for dose accumulation appears, on the basis of neutrons alone, to exceed the doses operators receive from field operation.

The full extent of doses from both neutron and gamma radiation was examined in a study utilizing BD-gamma and BD-100 neutron bubble detectors. A maintenance operator was monitored during the routine annual servicing of four moisture-density gauges, with three sets of BD-100 and BD-gamma dosimeters. The dosimeters were attached to the forearms above the wrist and to the waist. Monitoring took place over a 2½ hour period and all gauges were in a good state of repair. Dosimetry results are given in Table 21. Operator W activities are noted in Table 22. The results* indicate that the neutron and gamma radiation doses are approximately equivalent and the magnitude of the neutron dose is similar to that experienced by operator M. Doses to the extremities are approximately a factor of two higher.

5. Discussion

Observation during the field studies indicated that doses to moisture-density gauge operators are largely influenced by the requirements of the particular gauge application and the methods and times used by the operators to transport the gauge.

Gauge cleaning operations were relatively rare among the gauge users in terms of the number of measurements made on a seasonal basis. None of the gauge operators reported the need to clean the shutter mechanism more than a few times per season. In the previous section, operator doses during cleaning operations were identified as being approximately the same as would be accrued during a gauge use. With operators typically making from 1500 to 2500 measurements per year, the doses to field operators arising from routine cleaning are between 0.1% and 1% of their total annual dose. Even if gauge cleaning was performed on a daily basis throughout the operating season, it is unlikely that the operation would account for more than 10% of the annual operator dose.

* BD-gamma detectors respond to neutrons with a response factor approximately 10% of that for the gamma radiation.

Operator dose was a direct consequence of:

- 1) the radiation fields in the vicinity of the moisture-density gauge;
- 2) the length of time the moisture-density gauge had to be carried;
- 3) how the gauge was transported (distance from the gauge operator);
- 4) the number of measurements made by the operator.

Each of the above is indirectly related to the physical characteristics of a work site.

A moisture-density gauge operator is closest to the gauge when it is actually being carried. The need to carry the gauge was usually dependent upon whether a vehicle could be used to move the gauge from one measurement location to another. In many road construction applications, for instance, vehicle access to measurement locations was usually available and only limited hand-carrying by the operator was necessary. Hand-carrying affected extremity doses. Generally, many of the TLDs and DRDs indicated responses above their lower limits of detection for the hand and foot extremity dosimeter positions which were located on the side of the body used to carry the gauge.

Figure 11 gives a general indication of the differences in the gamma radiation fields which can be expected with different gauge configurations. For individual measurements, actual gauge configuration was determined by site requirements. As an example, depth of the source in the direct-transmission mode was a function of the layer of soil which was being compacted - effectively a site-based criteria and a consequence of the quality assurance program for the specific site. Data in Figure 11 are a compilation of the radiation dose rates observed during the field studies in central and western Canada. Most gauge applications were made in the direct-transmission mode, at 15 cm and 20 cm depths.

Doses arising from gauge transport in vehicles can be significant for some users. In 5 of the 18 gauge operators in the Central Canada and Western field studies, transportation accounted for the highest dose.

Including the doses received by simply carrying the gauge from measurement location to measurement location with the transportation dose, none of the operators had higher doses through direct operation of the gauge alone. Figure 12 gives a relative indication of the contribution to operator dose for each of the categories of transportation, carrying, and usage. The data are derived by normalizing the total dose in each group by the total number of measurements made. Data used to generate Figure 12 were derived from the direct gamma radiation survey estimates of operator dose and do not include neutron dose*.

Doses to the extremities were the most difficult to evaluate in the low dose environments of moisture-density gauge operator. Insufficient data were generated by the TLD/DRD results to draw any significant conclusions about the

* Only Central Canada and Western Canada have sufficient data sets to provide the discrimination among exposure categories. Neutron dose would increase the carry dose only. The magnitude of the increase was not measurable but can be estimated from Table 2.

magnitude of dose. The radiation field characteristics change from 1:1 near the gauge surface to 100:1 one meter away. CR-39 track-etch detectors provided little insight into operator extremity dose; they were used largely as qualitative indicators of exposure rather than quantitative tools, for the exposure range experienced.

Neutron and gamma bubble detector results, particularly for operators T and U, give the best indication of the differences between extremity dose and whole body dose. Gamma doses to the feet/ankle area can be higher by a factor of 30 with respect to the whole body dose registered by a trunk dosimeter. This would generally occur in the leg on the side of the body where the gauge is carried, and in the leg in the forward position when crouched in front of the gauge. If the dose to the lower extremities is averaged, then it would be of the order of 5 times the whole body dose. Doses to the hands are nearly equal to the trunk dose; this can be expected from purely geometrical considerations.

The level of operator dose in each of the exposure categories of use and transport can be described by the normalized distributions given in Figures 13 and 14. Both the unit transportation dose and gamma radiation doses follow log normal distributions with the following statistics.

Carry and operation	GM = 1220 nGy ⁺
	GSD = 1.4
Transportation	GM = 312 nGy ⁺
	GSD = 4.5

If the geometric mean dose is scaled according to the ratios of average extremity exposures (gamma) to whole body dose observed for operator U, a gamma dose distribution for average extremity exposure can be derived. These are indicated in Figure 14. The maximum is for a single extremity (normally one of the feet) and is indicated by a dashed line.

Actual annual operator dose is a direct consequence of the frequency of use of the device. Each of the participants was asked to indicate the number of actual measurements made in a year. However, none had the data in an easily retrievable form, nor was it expected that recorded applications would reveal relevant information. For example, in soil compaction, quality assurance is the most frequent application, and a single recorded moisture and density result was often based on a series of measurements. A measurement is taken and the material then recompactd with another measurement taken until a satisfactory level is achieved. Two or more measurements are made before the accepted result is recorded. Such events were commonly observed during the field work. Consequently, a review of records would be inappropriate for establishing annual usage.

Many of the operators considered the study day to be rather typical of their work load. If the distribution of measurements made per day by all operators is examined (Figure 15), the geometric mean of the distribution (GM = 13.8 GSD 2.18) and the length of the construction season (27-30 weeks) would indicate that operators use the gauges typically around 1700 to 2000 times per

+ per gauge operation

year. This is in agreement with the subjective estimates provided by operators during the field work. The maximum number of measurements made on an annual basis was estimated by an operator (K) who performed exclusively backscatter measurements ($n = 3000$).

The overall distribution of operator dose due to gamma radiation produced by the gauges is given in Figure 16. Based on the number of measurements made annually and the short season of frequent use, one can conclude that typical moisture-density gauge operators do not receive annual doses much in excess of 1 mSv. Neutron exposure determined by CR-39 and BD-100 bubble detectors indicate that neutron doses are much lower, with the exception of individuals using asphalt gauges on a routine basis along with the moisture-density gauge. For asphalt gauges, which are transported with a moisture-density gauge to construction sites and used daily, radiation exposure to the operator to neutrons could be more significant than gamma exposures.

Maintainers of nuclear gauges are likely to exceed the 1 mSv dose that gauge operators receive on an annual basis, and possibly exceed 5 mSv if gauge repair is performed on a frequent basis. Much of the dose would be due to neutron exposure.

6. Summary and Recommendations

Moisture-density gauges are widely used throughout the construction industry for quality assurance testing of construction materials, soils, asphalt, and concrete. Most applications are concerned with either the compaction of these materials or the identification of voids.

Twenty-four operators and maintainers of moisture-density gauges were monitored for radiation dose arising from use and maintenance of the gauges. Monitoring took place in the Western (Alberta) Central (Ontario) and Eastern (Quebec) regions of the country in order to obtain a diversity of work environments and use applications.

Measurements of gamma doses to the body and extremities were estimated using a combination of passive dosimetry: thermoluminescent and electronic dosimeters for gamma radiation; CR-39 track-etch detectors for neutrons; active dosimetry consisting of radiation field mapping and time accounting.

Newly developed bubble detector dosimetry technology was included in the study program in various degrees. Initially it was used to estimate neutron whole body dose (Central and Western studies). Then, because of the considerable improvement in sensitivity (1 μ Sv), it replaced all conventional dosimetry methods for operator dose studies in the Eastern study and a maintenance study. The detectors, BD-100 neutron detectors and BD-gamma dosimeters, proved extremely valuable in indoor environments in low physical work situations, but were difficult to use without temperature control. Generally, the active dosimetry methods provided the only complete data sets for all operators. Most conventional passive dosimetry results were below lower limits of detection.

Gamma dose distributions for various aspects of gauge use were identified. Normalized doses (per unit operation) were log-normally distributed.

gauge usage	GM = 1.2 μ Gy	GSD = 1.4
transportation	GM = 310 nGy	GSD = 4.5

The distribution of measurements among the study population indicated that operators make 13.8 measurements per day (geometric mean, geometric standard deviation 2.12). Operators use the gauge on a routine basis for 27-30 weeks annually.

The body dose among all of the operators was, in general, less than 1 mSv with the exception of one operator also using a nuclear-based asphalt gauge.

Extremity doses above the levels recorded by body dosimeters occurred generally in the feet area or the hand and foot area corresponding to the side of the body closest to where the gauge was carried.

Bubble detector results indicated that neutron doses to the extremities were low - less than 2 μ Sv. Gamma doses to the feet were approximately five times the body dose. The dose to the hands appears to be approximately the same as the body dose.

Doses arising from operators cleaning the shutter mechanism were negligible compared to the doses arising from field use.

Doses to gauge maintainers appear to be the same for neutrons and gamma radiation, with hands-on work of 15 minutes duration being approximately equivalent in terms of accrued dose, to the dose an operator receives during one day of field operation. Maintenance personnel are more likely to receive doses in excess of 5 mSv.

Doses to operators can be minimized by:

- 1) positioning the gauge such that the sides with the lowest dose rates are orientated towards the driver or operator during transportation
- 2) keeping the gauge more than 1 m away from the operator during hole preparation
- 3) minimizing the distance the source-rod is extended out of the instrument housing before insertion into the measurement access hole
- 4) moving away from the gauge when doing computations.

Recommendations

1. Individuals regularly maintaining nuclear-based gauges should be designated Atomic Radiation Workers. Monitoring should consider the contribution of neutrons to total dose.

2. Individuals using both asphalt gauges and moisture-density gauges should be studied to assess their level of dose. Monitoring should be based on temperature compensated bubble detector technology.

References

1. Instrument Operating manuals;
Technical Manual BRC-82 Campbell Pacific Nuclear Corporation 3400-B
Series Surface Moisture-Density Gauges, Troxler International Humboldt
5001 Operating Manual - Humboldt
2. IAEA, Neutron Moisture Gauges, Technical Report No. 112, Vienna 1970.
3. Atomic Energy Control Act, 1978 Canada Gazette Part II, Vol. 112, No. 2.
4. Atomic Energy Control Board, Consultative Document C-83, "Proposed General Amendments to the Atomic Energy Control Regulations", 1986 April 28.

GLOSSARY

absorbed dose (D):	The energy (exclusive of rest mass) deposited by ionizing radiation per unit target mass. The S.I. unit is the gray . The former unit was the rad; 1 gray = 100 rad.
active dosimetry:	Dosimetry employing detectors which give immediate readings of dosimetric quantities--used in this work to mean the immediate determination of dose rate.
activity:	The statistically expected number of spontaneous transitions from one nuclear species to another per unit time. The S.I. unit is the becquerel (Bq) . The former unit still sometimes used is the curie (Ci) .
alarming dosimeter:	An electronic dosimeter usually giving an immediate readout of accumulated gamma dose and which is designed to give an audible alarm when a pre-set dose is exceeded.
atomic radiation worker (ARW):	Any person who in the course of his/her work is likely to receive a dose of ionizing radiation in excess of doses specified in the Atomic Energy Control Act. The Regulations of the Act give details of employer obligations regarding ARW's.
background:	A general term describing an ubiquitous radiation field which may be natural background radiation (from cosmic rays and primordial terrestrial nuclides) and may include technologically enhanced and man-made sources.
backscatter:	Radiation other than that emanating directly from the source, and generally refers to Compton-scattered radiation which is roughly directionally-opposite that of the primary radiation .
becquerel (Bq):	The S.I. unit of activity equal to one statistically expected nuclear transition per second. Sources of high activity are often given in MBq (10^6 Bq) or GBq (10^9 Bq).
bubble detector:	A radiation detector consisting of a vial containing a polymer super-saturated with a gas solute. When exposed to certain types of radiation , bubbles will form in the polymer in proportion to the dose delivered.

curie (Ci):	The old unit of activity. $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$.
direct reading dosimeter (DRD):	A dosimeter which gives an immediate digital or analog readout of the accumulated dose.
dose:	A general term used in short for something more specific such as absorbed dose, dose equivalent or effective dose equivalent. In this work, the term dose is generally used to mean either dose equivalent or effective dose equivalent, depending on the context.
dose equivalent (H):	The product of absorbed dose (D) and the quality factor (Q) of the radiation involved. Dose equivalent is the quantity that most closely relates the biological effect of the radiation to the tissue exposed. The S.I. unit is the sievert. The former unit was the rem; 1 sievert = 100 rem.
dose limits:	The values of dose equivalent and effective dose equivalent which must not be exceeded. Dose limits are recommended by the International Commission on Radiological Protection; the proposed limits of the Atomic Energy Control Board are based on these recommendations.
dosimeter:	A device used to measure any quantity that can be directly related to either absorbed dose, dose equivalent, or effective dose equivalent.
dosimetry:	The determination or estimation of dose equivalent or related quantities.
effective dose equivalent (H_E):	A quantity defined as $H_E = \sum W_T H_T$ where H_T is the dose equivalent in tissue T, and W_T is a weighting factor for tissue T; weighting factors are specified by the International Commission on Radiological Protection, based on tissue radiosensitivities. The summation is performed over all tissues, T. The effective dose equivalent is an additive quantity and is the quantity directly related to stochastic risk. Units are those of dose equivalent.
exposure:	A term used in radiation protection both in a specifically defined quantitative sense (in terms of the ability of an X-ray or gamma-ray field to ionize air), and also in a general sense. In this work exposure is used in the general sense; depending on the context, it is used synonymously with dose.

fast neutrons:	Neutrons with high kinetic energies.
gamma dose:	The dose delivered by the secondary charged particles resulting directly or indirectly from the interactions of a gamma-ray field with matter.
gray (Gy):	The S.I. unit of absorbed dose . $1 \text{ Gy} = 1 \text{ J.kg}^{-1} = 100 \text{ rad}$.
ionizing radiation:	For the purposes of radiation protection, radiation capable of producing ion pairs in tissue.
mass attenuation coefficient (μ/ρ):	For a specific uncharged ionizing radiation , the interaction probability per unit mass thickness of the matter irradiated. The S.I. units are $\text{m}^2.\text{kg}^{-1}$.
moderation:	The process whereby neutrons lose kinetic energy as a result of multiple elastic collisions with the constituent atomic nuclei of the moderator.
neutron dose:	The dose delivered by the secondary charged particles resulting directly or indirectly from the interactions of a neutron field with matter.
passive dosimetry:	Dosimetry employing dosimeters which, when read sometime after their exposure, give estimates of dosimetric quantities--used in this work to mean the determination of the integrated dose rather than the dose rate .
quality factor (Q):	A factor that weights the absorbed dose to account for the relative biological effectiveness for a given absorbed dose of the type of radiation involved. Values of Q are specified by the International Commission on Radiological Protection.
radiation:	In this work, radiation means ionizing radiation .
reference standards:	Materials of known composition, density, and hydrogen content with which the interactions of ionizing radiation are known.
S.I.:	Système International
sievert (Sv):	The S.I. unit of dose equivalent and effective dose equivalent . $1 \text{ Sv} = 1 \text{ J.kg}^{-1} = 100 \text{ rem}$.

thermal neutrons:	Neutrons with kinetic energies so low that they are in thermal equilibrium with their surroundings.
thermoluminescence (TL):	The thermally stimulated emission of light-quanta from the de-excitation of previously trapped charge carriers. It occurs at temperatures well below those necessary for incandescence.
thermoluminescent dosimeter (TLD):	A dosimeter employing crystals which exhibit thermoluminescence when subsequently heated (during reading), the amount of thermoluminescence being proportional to the absorbed dose delivered to the crystals during field use.
time constant:	A time interval related to the time that a meter takes to respond to a change in the quantity being measured. It is governed by capacitance and resistance in the meter's electronic circuit.
track-etch detector:	A detector of particles of ionizing radiation that, upon the particles' interactions with the detector medium, can render sufficiently dense tracks of ionization such that the tracks can subsequently be chemically etched and counted. Proton recoil from fast-neutron interactions causes such tracks, their number being proportional to the neutron dose .
transportation index:	Transport index as defined in the Transport Packaging of Radioactive Materials Regulations of the Atomic Energy Control Act and a number therein defined as an indicator of the relative magnitude of a hazard based on, among other things, the size of the package and the maximum radiation levels a set distance from the external surface of the package.
type-A package:	A package defined as such in the Transport Packaging of Radioactive Materials Regulations of the Atomic Energy Control Act, based on the package's ability to meet tests relevant for normal conditions of transport, and whose hazard is controlled by inventory limits.

Table 1: Specifications For Some Commercial Moisture-Density Gauges

Manufacturer	Model Series/ Model	(1) Weight (kg)	(2) Dimensions (cm)	Radiation Sources	Activity (MBq)	(3) Maximum Radiation (μ Sv/h)
Troxler	3400-B/ 3401	16	37x30x50	Cs-137 Am-241 Be	300 1480	150
	3411					
	3440					
Campbell Pacific (CPN)	CPN-MC1	15	36x23x56	Cs-137 Am-241 Be	370 1850	150
	CPN-MC2					
Humboldt	5001	18	40x22x55	Cs-137 Am-241 Be	370 1850	140

- (1) weight is for gauges only
 (2) nominal dimensions with source rod in storage position
 (3) approximate radiation levels expected at the surface of the
 moisture-density gauge

Table 2: Dose-Equivalent Rates In The Vicinity of Several
Commercial Moisture-Density Gauges (1)

	(μSv/h)		
	TROXLER 3400 SERIES	CAMPBELL PACIFIC MC1/MC2	HUMBOLDT 5001
FRONT	50 (0.7)		40 (0.6)
BACK	150 (0.3)		140 (0.9)
SIDES	140 (1.1)		90 (0.8)
TOP	65 (0.9)		130 (0.8)
BOTTOM	120 (0.6)		100 (0.7)
HANDLE	5.2		6.2 (0.2)
PANEL		50	

(1) manufacturers literature

() denote dose-equivalents at 1 m from gauge surface

Table 3: General Types of Gauge Maintenance Operations

Activity	Hazard
1. Gauge Cleaning - removal of dirt in the source cavity and from the source rod scraper ring [source rod not removed]	gamma and neutron hazards present, gamma beam of several tens of mGy present after shutter shield is removed
2. Gauge Cleaning Maintenance - removal of source rod - removal of dirt from source cavity, trigger mechanism source rod bearings - lubrication	high gamma radiation during rod removal and transfer neutron hazard for other operations
3. Maintenance Repair - scalers, detectors microprocessors, batteries	low energy gamma radiation and neutrons of the order of 10-20 Sv/h at the body location

Table 4: Moisture-Density Gauge Operator Activities Central Canada Field Study

Operator	Gauge	Application	Measurement Configuration	Soil/Material	Activities
A	Troxler 3401-B	highway construction base-compaction	direct transmission 10 cm; 15.2 cm 20 cm	Gravel: granular A granular B, local soil	no transportation with gauge off work site (site storage); gauge standardized, transported at work site behind passenger seat of a compact van to measurement locations.
B	Troxler 3401-B	highway construction base-compaction	direct transmission 15.2 cm	sandy clay	no transportation with gauge off work site (site storage) gauge standardized; transported within work site unpowered at right rear of full size van.
C	Troxler 3401-B	highway construction base-compaction	direct transmission 15.2 cm	Gravel: granular A; granular B	gauge stored at site - no off site transport; gauge standardized; transported at work site on the floor of the passenger side of pick-up truck
D	Troxler 3401-B	cleaning			gauge cleaning procedure
E	Troxler 3401-B	road surface compaction; trench compaction	direct transmission 20 cm	course compacted gravel backfill	gauge transported in shipping crate in trunk of automobile; unpacked gauge carried to trunk; three construction sites visited; standardized twice; cleaned at end of day
F	Troxler 3401-B	warehouse slab foundation; road construction; pipe trench	direct transmission 15.2 cm; 20 cm	compact gravel	gauge transported in shipping crate in trunk of automobile; unpacked gauge carried to trunk; three construction sites visited; cleaned at end of day
G	Troxler 3401	trench compaction; asphalt	direct transmission 20 cm backscatter	compact granular A asphalt	gauge hand carried to automobile, placed in shipping crate in trunk to transport to work sites; two work sites; cleaned at end of day
H	Humboldt 5001	road construction; subdivision/industrial Park	direct transmission 20 cm backscatter	compact granular A asphalt	gauge standardized at office then transported to work site in trunk of car. Gauge removed from packing crate for transport at construction site.
I	GPR-MCI	road construction residential subdivision	direct transmission	clay - limestone	gauge standardized at office then transported to work site in rear of pick-up truck.
J	Humboldt 5001	factory base compaction	direct transmission 10 cm	compact gravel	gauge stored at construction site, standardized and moved to measurement locations at the tractor site in the rear of a hatchback compact automobile.

Table 5: Radiation Doses To The Body For Moisture-Density Gauge Operations
From Direct Surveys - Central Canada Study

Operator	Gauge	Medium	Measurement Depth (cm)	Number of Uses(N)	Dose (nGy)
A	Troxler	standard	0.0	1	
		granular A	10.2	4	220
		granular B	10.2	1	24
		earth	10.2	1	2
		granular A	15.2	3	91
		earth	15.2	3	144
		granular B	20.3	1	43
		earth	20.3	1	18
B	Troxler	standard	0.0	1	40
		earth	15.2	1	39
		sandy clay	15.2	9	446
C	Troxler	standard	0.0	1	3
		granular A	15.2	8	328
		granular B	15.2	6	260
E	Troxler	standard	0.0	2	65
		gravel	20.3	14	421
		course gravel	20.3	6	202
		gravel/crushed rock	20.3	9	472
F	Troxler	standard	0.0	1	7
		gravel	15.2	7	477
		earth/fill	20.3	6	385
		gravel	20.3	3	133
G	Troxler	standard	0.0	1	33
		gravel	20.3	22	3999
H	Humboldt	asphalt	bs (1)	44	1264
		granular A	15.2	18	787
I	CPN-MC1	gravel	20.3	5	336
J	Humboldt	gravel	10.2	3	15

(1) bs - backscatter operation

Table 6: Estimated Gamma Radiation Doses To The Body For Moving and Transporting Moisture-Density Gauges -Central Canada Study

Operator	Number of Uses	Carrying Gauge	Vehicle Transportation	
		dose nGy	time (hours)	dose nGy
A	15	722	1.3	1560
B	11	1264	0.3	36
C	15	2153	1.6	2240
E	31	5810	4.3	1290
F	17	1245	2.8	855
G	23	322	0.5	150
H	62	*	1	1200
I	5	*	1	200
J	3	*	0.1	10

* insufficient data recorded to make estimate

Table 7: Total Estimated Single Day Gamma Radiation Dose
To the Body -Central Canada Study

Operator	Dose Estimate (μ Gy)
A	2.8
B	1.8
C	5.0
E	8.3
F	3.1
G	4.5
H	8.5
I	0.96
J	0.28

* Operators I J K estimates include values estimated for carrying
gauges-- the average gamma dose for gauge carrying for all
operators excluding I J K is 84 nGy/gauge use

Table 8: TLD, CR-39, and DRD Results for Body and Extremities - Central Canada Study

OPERATOR	LEFT HAND TLD (μSv) DRD (μGy) CR-39 (μSv)	RIGHT HAND TLD (μSv) DRD (μGy) CR-39 (μSv)	WHOLE BODY TLD (μSv) DRD (μGy) CR-39 (μSv)	LEFT FOOT TLD (μSv) DRD (μGy) CR-39 (μSv)	RIGHT FOOT TLD (μSv) DRD (μGy) CR-39 (μSv)
A					
B					
C					
D					
E			10	10	10
F	10			10	
G		10	10	20	20
H					
I					
J					

Table 9: Moisture Density Gauge Operator Activities Western Canada Field Study

Operator	Gauge	Application	Measurement Configuration	Soil/Material	Activities
K	CPM-MC1	road construction	backscatter	compacted gravel	gauge picked up from storage area and transported to work site in rear of pick-up truck; transported at site in pick-up truck in packing crate.
L	CPM-MC2	road construction	backscatter	asphalt	gauge picked up at storage centre and transported to work site. Equipment failure during field measurements. Instrument returned for repair.
M	CPM-MC2	maintenance			gauge cleaned and lubricated. Operator also maintains Troxler 2256 asphalt gauges.
N	Troxler 3401-B	foundation base compaction	direct transmission 30.5 cm	compacted gravel	Operator had gauge at work site; gauge transported around site in vehicle
O	CPM-MC1	road construction	backscatter	asphalt	Operator monitoring asphalt with Troxler 2226 asphalt gauge. Demonstrated 10 hole asphalt test pattern with moisture-density gauge.
P	Troxler 3401-B	foundation base compaction	direct transmission 30.5 cm	compacted sandy silt	gauge stored at central office, picked up and transported to two sites in rear of pick-up truck. Standardized at first site.
Q	Troxler 3401-B	road construction building slab foundation	direct transmission 25.4 cm, 20 cm, 15.4 cm	clay earth granular B	gauge picked up at office, transported in rear of pick-up truck outside shipping crate traveled to several work sites during the day. Returning.
R	Troxler 3401-B	road construction	direct transmission 20 cm, 5 cm	compacted clay/gravel concrete curbs	gauge picked up at office transported in the rear of a van outside packaging single work site, returned at end of day. Several sites visited.
S	CPM-MC2	road construction	direct transmission	compacted gravel	gauge picked up at office, transported in vehicle to work sites.

Table 10: Doses For Moisture-Density Gauge Operation
From Direct Surveys - Western Canada Study

Operator	Gauge	Medium	Depth (cm)	Number of Measurements	Dose (nGy)
K	CPN-MC1	standard	0	2	174
		granular A	bs	11	347
		silty clay	bs	3	86
		cold mix	bs	1	51
L	CPN-MC1	asphalt	bs	4	244
N	Troxler	granular B	30	18	30
O	CPN-MC1	asphalt	bs	4	244
P	Troxler	silty clay	30	4	53
		silty sand	30	3	30
Q	Troxler	silty clay	25	11	1612
		granular B	20	6	165
R	Troxler	standard	0	1	10
		concrete curb	5	28	749
		jersey barrier	5	1	167
S	Troxler	silty clay	20	7	390

bs - backscatter

* granular A ,granular B are grades of gravel
cold mix is a gravel oil mixture
standard is a polyethylene block

Table 11: Estimated Gamma Radiation Doses To The Body For Carrying
and Transporting Moisture-Density Gauges- Western Canada Study

Operator	Number of Uses N	Gauge Carrying	Transportation	
		dose (nGy)	time (hours)	dose (nGy)
K	17	760	1.9	760
L	4	30	0.6	300
N	18	1000	0	0
O	10	500	1	500
P	7	610	1	300
Q	17	540	2.6	2215
R	30	3083	2.7	2650
S	7	736	6.5	1280

Table 12: Total Estimated Single Day Radiation Dose
Western Canada Study

Operator	Dose Estimate (μ Gy)
K	2.2
L	0.57
N	1.0
O	1.5
P	1.0
Q	4.5
R	6.7
S	2.4

Table 14: Moisture-Density Gauge Operator Activities - Eastern Canada Study

Operator	Gauge	Application	Measurement Configuration	Soil/Material	Activities
T	Troxler 3411-B	slab foundation	direct transmission 10 cm, 15 cm	gravel	equipment stored at site; gauge transported on site on rear of an all terrain vehicle and returned to storage area.
U	Troxler 3411-B	slab foundations road construction	direct transmission backscatter	gravel	gauge cleaned at onset of work because of difficulties in source rod movement. Transported to work sites (3) in rear of compact auto unpackaged.
V	Troxler 344	road construction	backscatter	asphalt	gauge taken to site in automobile and measurements taken on a preestablished pattern on a recently laid asphalt surface computerized gauge - single button operation.

Table 15: Dose-Equivalents For Operator T Determined
From BD-Gamma Bubble Detectors

(μSv)					
Activity	left hand	right hand	waist	left foot	right foot
direct transmission 10 cm;15 cm 7 measurements	<1.6	0.2	1.5	<1.7	51
backscatter 3 measurements	0.7	0.7	0.7	2	.5

Table 16: Dose-Equivalents For Operator U Determined From
BD-Gamma Bubble Detectors

(μSv)					
Activity	left hand	right hand	waist	left foot	right foot
gauge cleaning	<0.2	<0.2	<0.2	<0.4	<0.2
direct transmission 3 measurements	8.6	2.5	2.3	6.7	8.1
travel to site 2 direct transmission 10 cm;15 cm 19 measurements at site	2.5	4.4	3.0	37	70
travel to site 3 direct transmission 4 measurements backscatter 15 measurements	*	*	*	*	*

* out of range temperature /large temperature fluctuations

Table 17: Dose-Equivalents For Operator V Determined from
BD-Gamma Bubble Detectors

(μSv)					
Activity	left hand	right hand	waist	left foot	right foot
travel to site	*	*	<3.8	*	*
backscatter 15 measurements	<5.9	<5.9	***	**	**
return to office	<0.5	4	<0.5	0.5	8.7

* large temperature shift due to operation of automobile heater
no estimate possible

** out of range temperature

*** low temperature -sensitivity 100 uSv

Table 18: Summary of Estimated Gamma Dose-Equivalents
For Operators T,U,V

Operator	Number of Measurements	(μSv)		
		hands/wrists	waist	ankles/feet
T	10	1.6	1.1	34
U	22	4.5	5.3	30
V		*	*	*

*insufficient data available for comparison

Table 19: Maintenance Operations Observed During Field Studies

Operator	Activity	Details
D	clean & check gauge after use by Operator C	source rod removed mechanical components cleaned and lubricated, unit reassembled and source rod reinstalled (30 minutes)
E	clean gauge after field use	bottom cover plate removed; shielding block removed; cleared (2-5 minutes) reassembled
F	clean gauge after field use	same as E (2 minutes)
G	clean gauge after field use	same as E (3.5 minutes)

Table 20 : Neutron Dose-Equivalents For Maintenance Operator M
(μSv)

Detector	left hand	right hand	waist	left foot	right foot
BD-100	24	44	35	*	*
CR-39	30	60	0.5	30	30

* none worn

Table 21: Neutron And Gamma Dose-Equivalents
For Maintenance Operator W

(μSv)

Detector	left hand	right hand	waist
BD-100 (neutrons)	12	11	14
BD-Gamma	17	19	11

Table 22: Operator W - Maintenance Activities

DESCRIPTION	
1	4 storage boxes cleaned then gauges stored in shielded storage area, gauge stored approximately 2 m away during activity
2	source leak tests, panel removed for the AmBe test
3	wiper ring removed, source rod removed, gauge moved to work bench for mechanical maintenance
4	shield blocks removed, bearing area, gauge exterior, shield block cavity cleaned
5	lubricated
6	reassembled

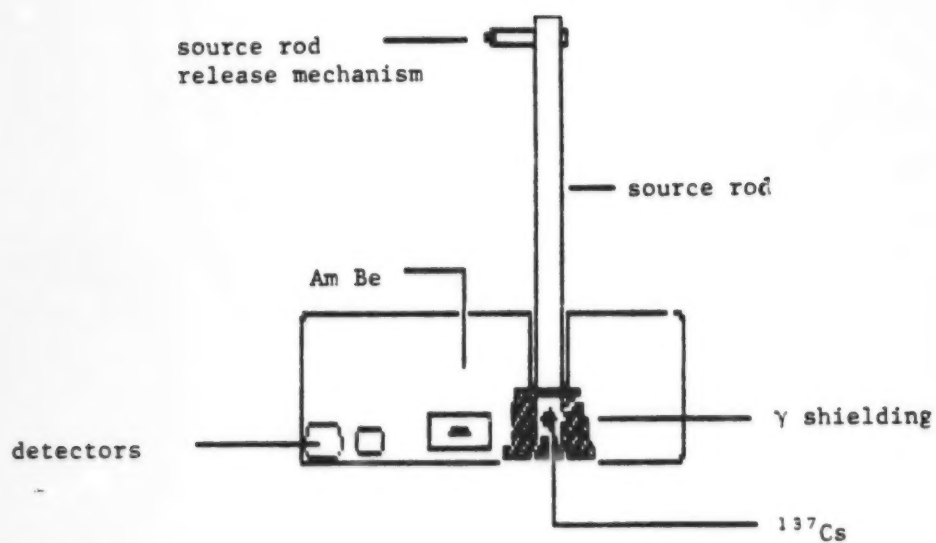


Figure 1: Generalized Configuration of a Portable Moisture-Density Gauge

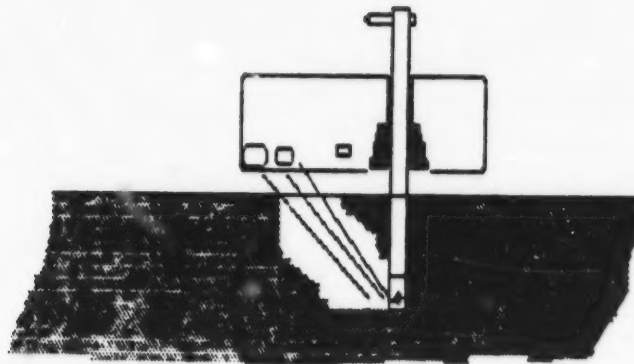


Figure 2: Moisture-Density Gauge Configuration In Direct Transmission Mode

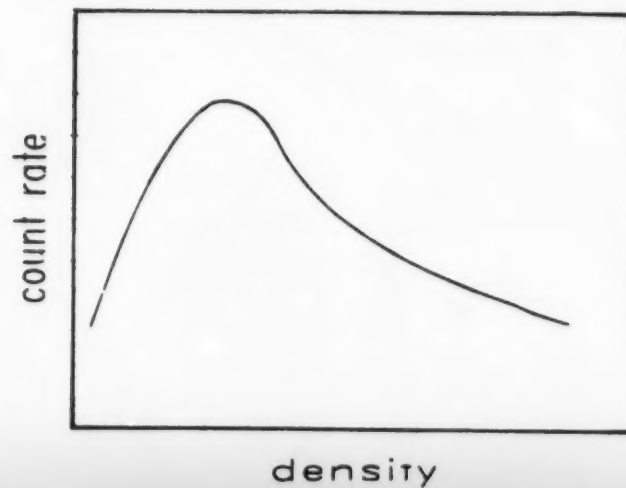


Figure 3: Response Functions For Moisture-Density Gauge Operation -- Direct Transmission

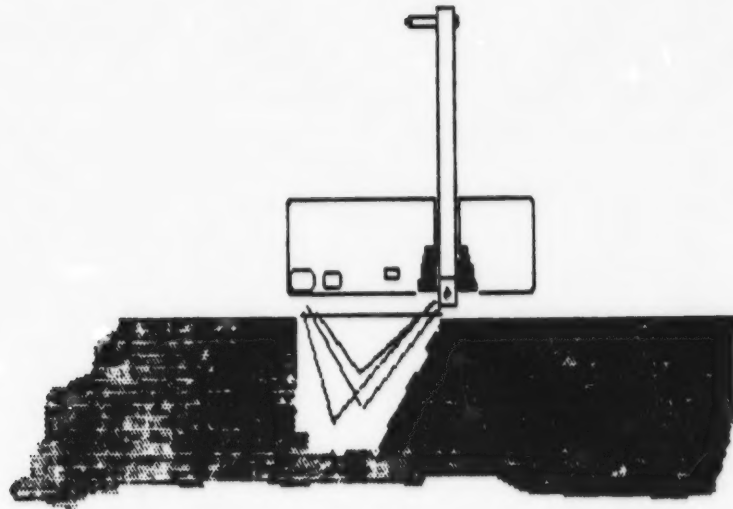


Figure 4: Moisture-Density Gauge Configuration In Backscatter Mode

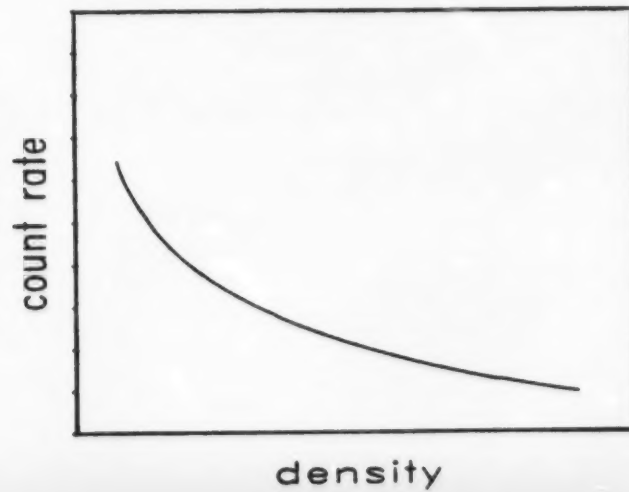


Figure 5: Response Functions For Moisture-Density Gauge Operation -- Backscatter

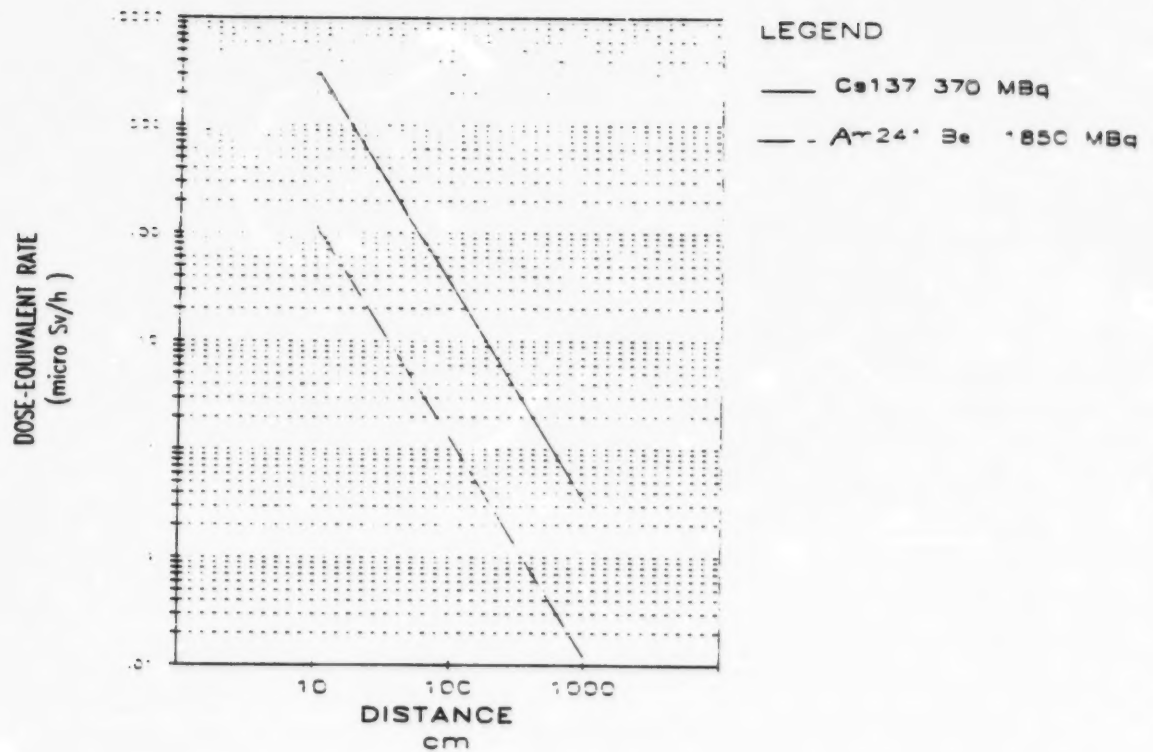


Figure 6: Radiation Characteristics From Unshielded Isotropic Sources Used In Portable Moisture Density Gauges

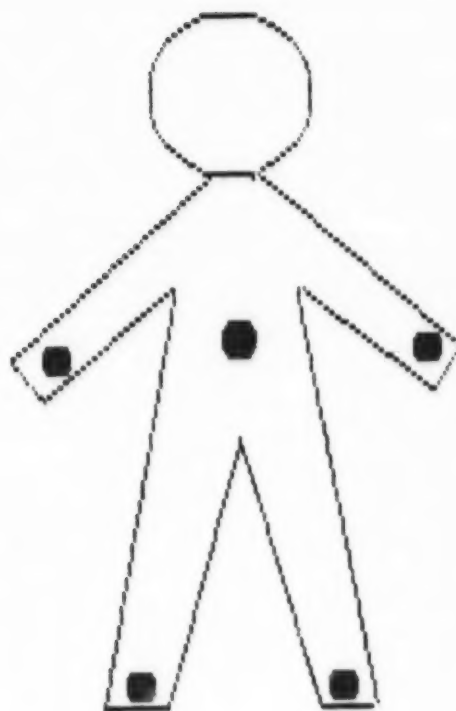


Figure 7: Position Of Dosimeters on Moisture Density Gauge Operators

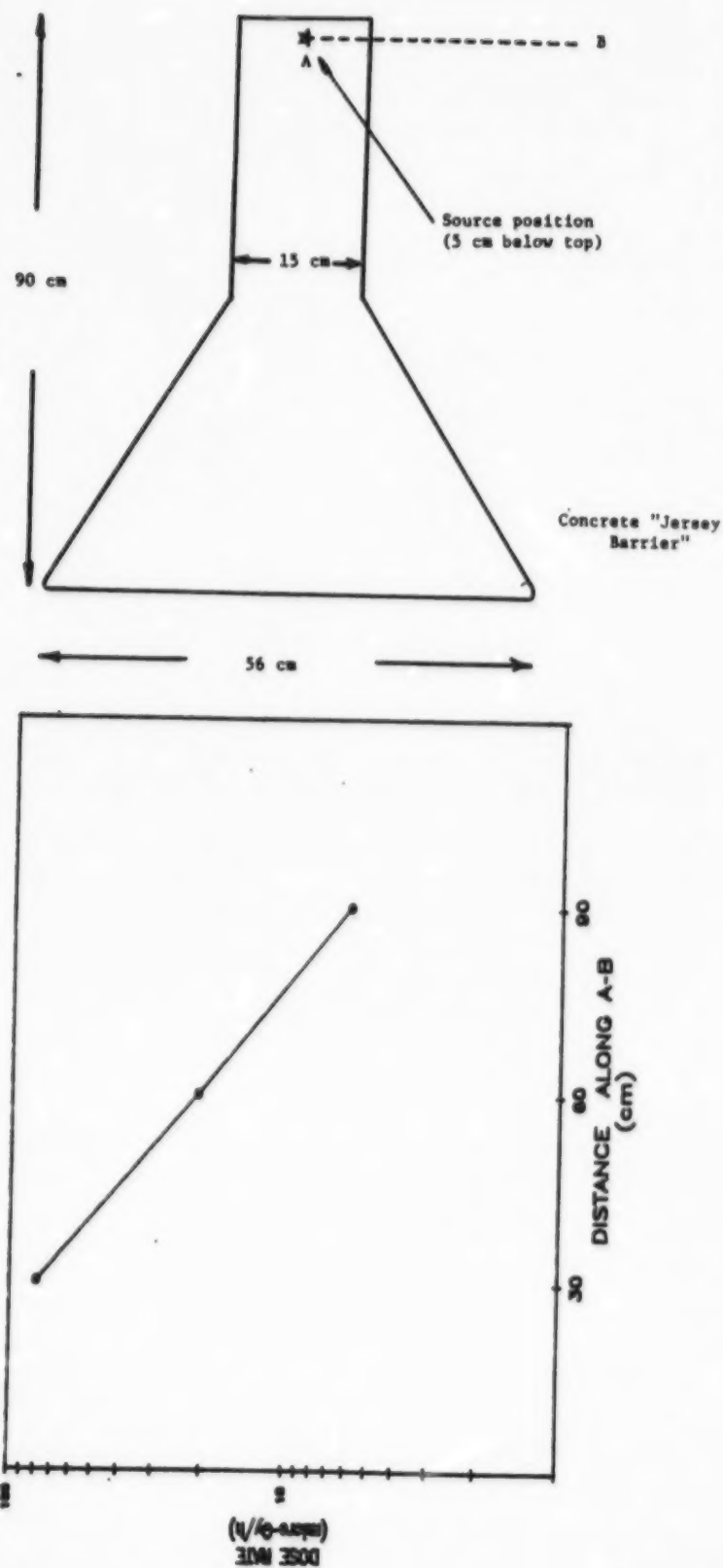


Figure 8: Radiation Fields in the Vicinity of a Concrete "Jersey Barrier" During Evaluation with a Commercial Moisture-Density Gauge

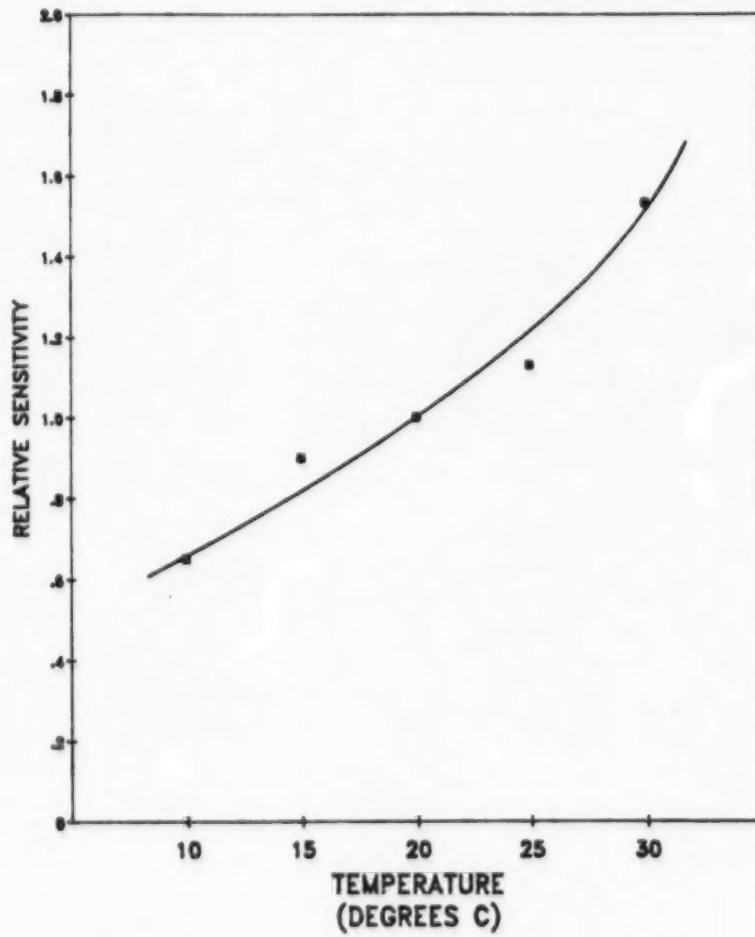


Figure 9: BD-100 Neutron Bubble Detector Temperature Response Curve

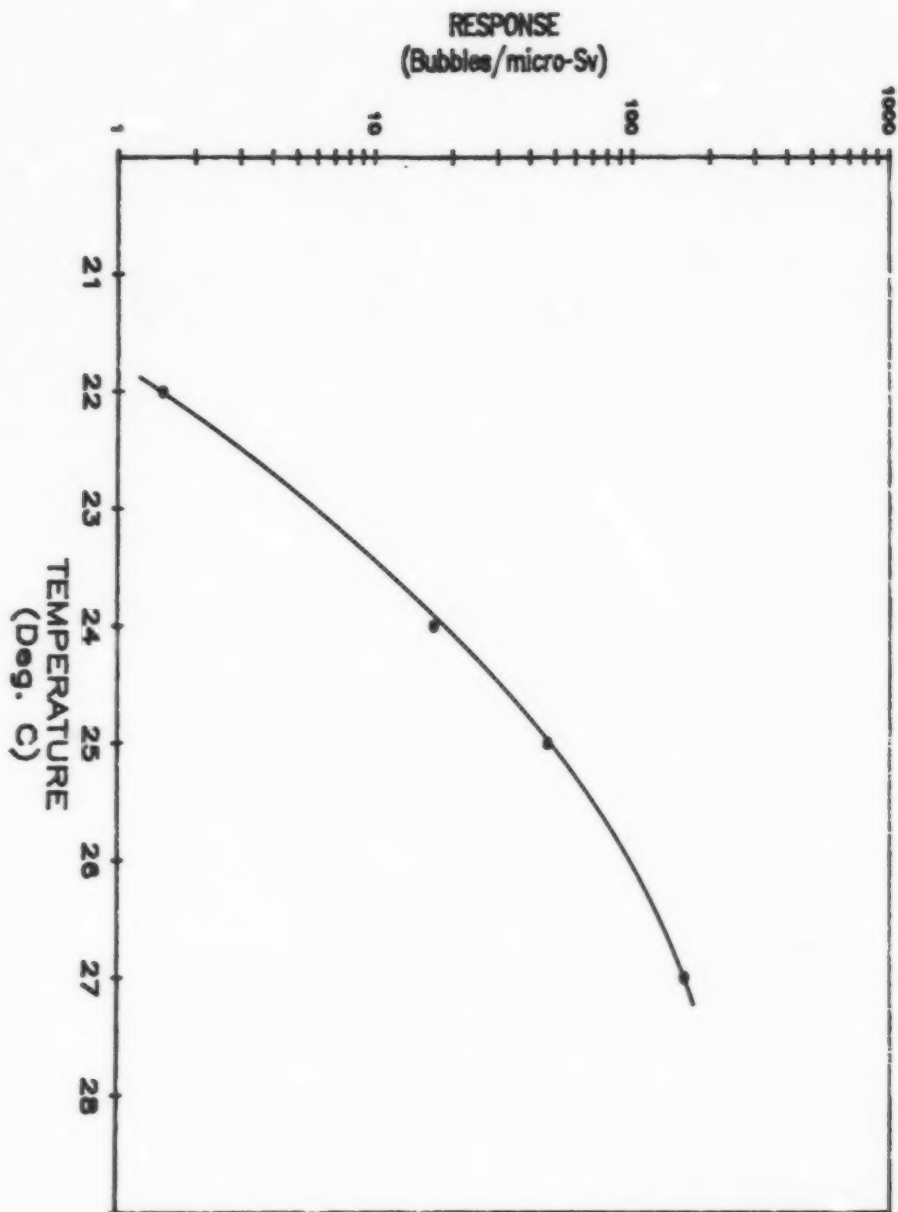


Figure 10: BD-Gamma, Gamma Radiation Bubble Detector Temperature Response Curve

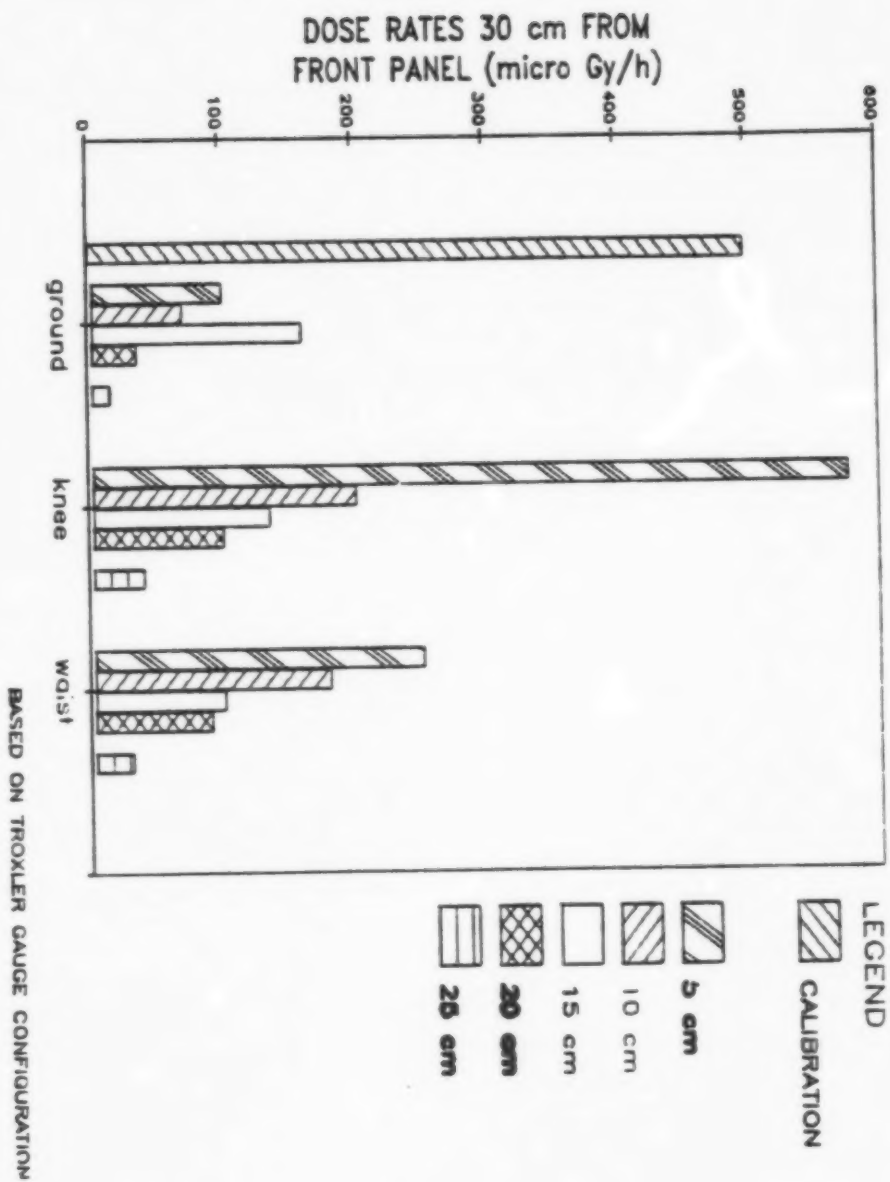


Figure 11: Dose Rates In The Vicinity Of Moisture
Density Gauges For Different Operating
Configurations

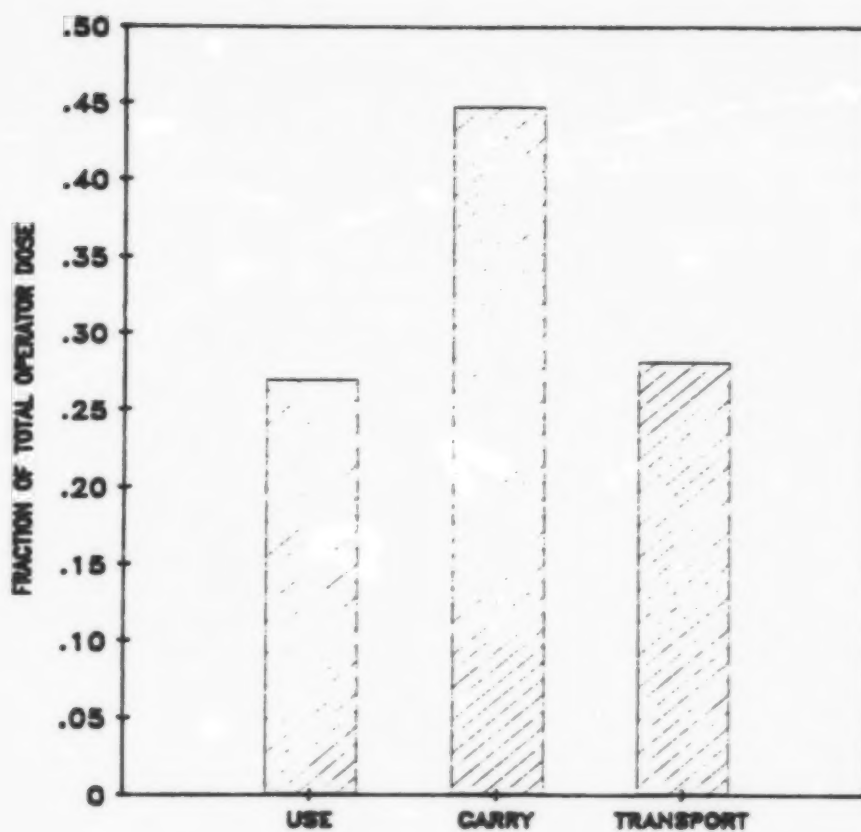


Figure 12: Contribution of Operator Activities
To Total Dose

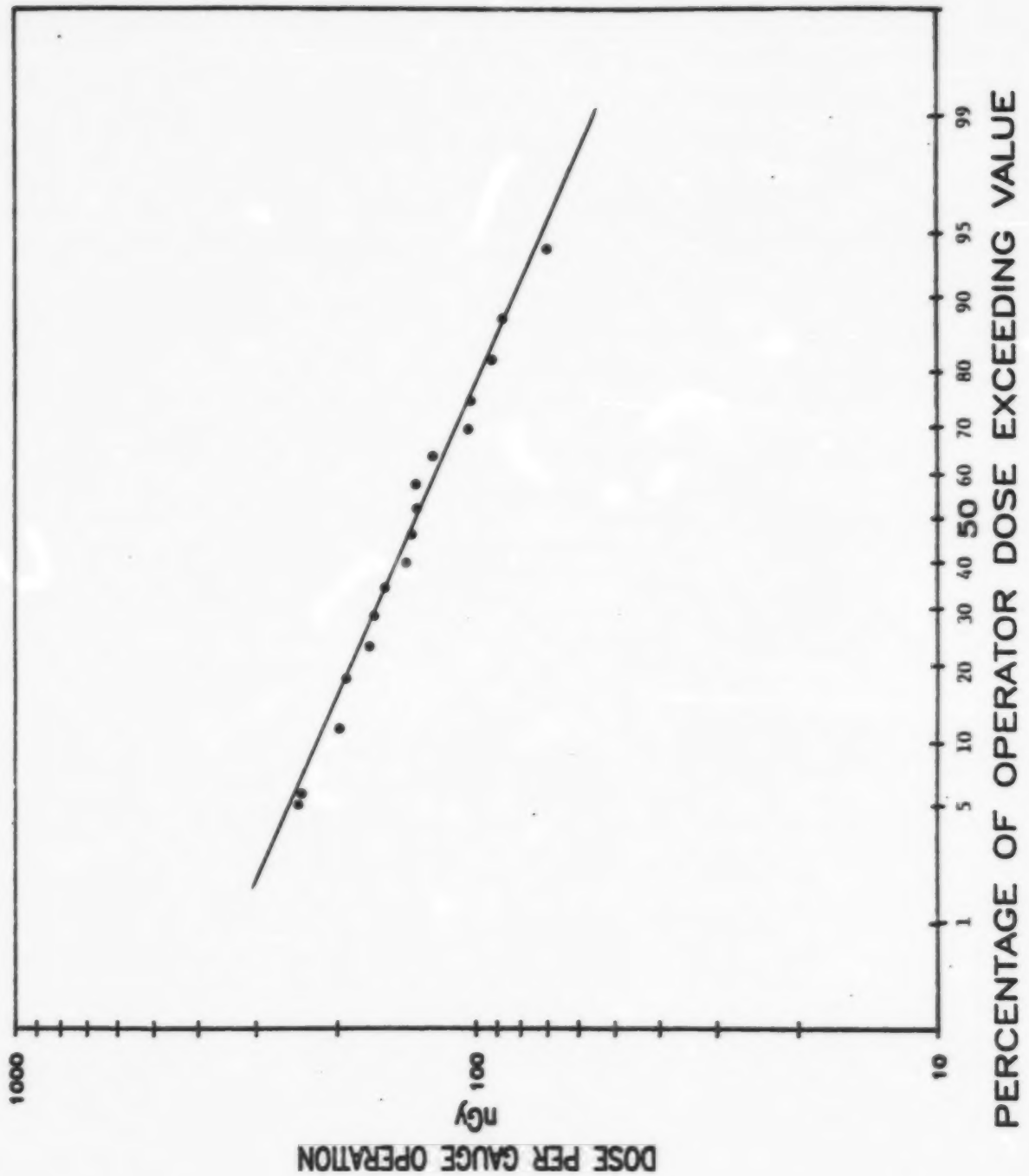


Figure 13: Doses to Operators Due to Moisture-Density Gauge Operation

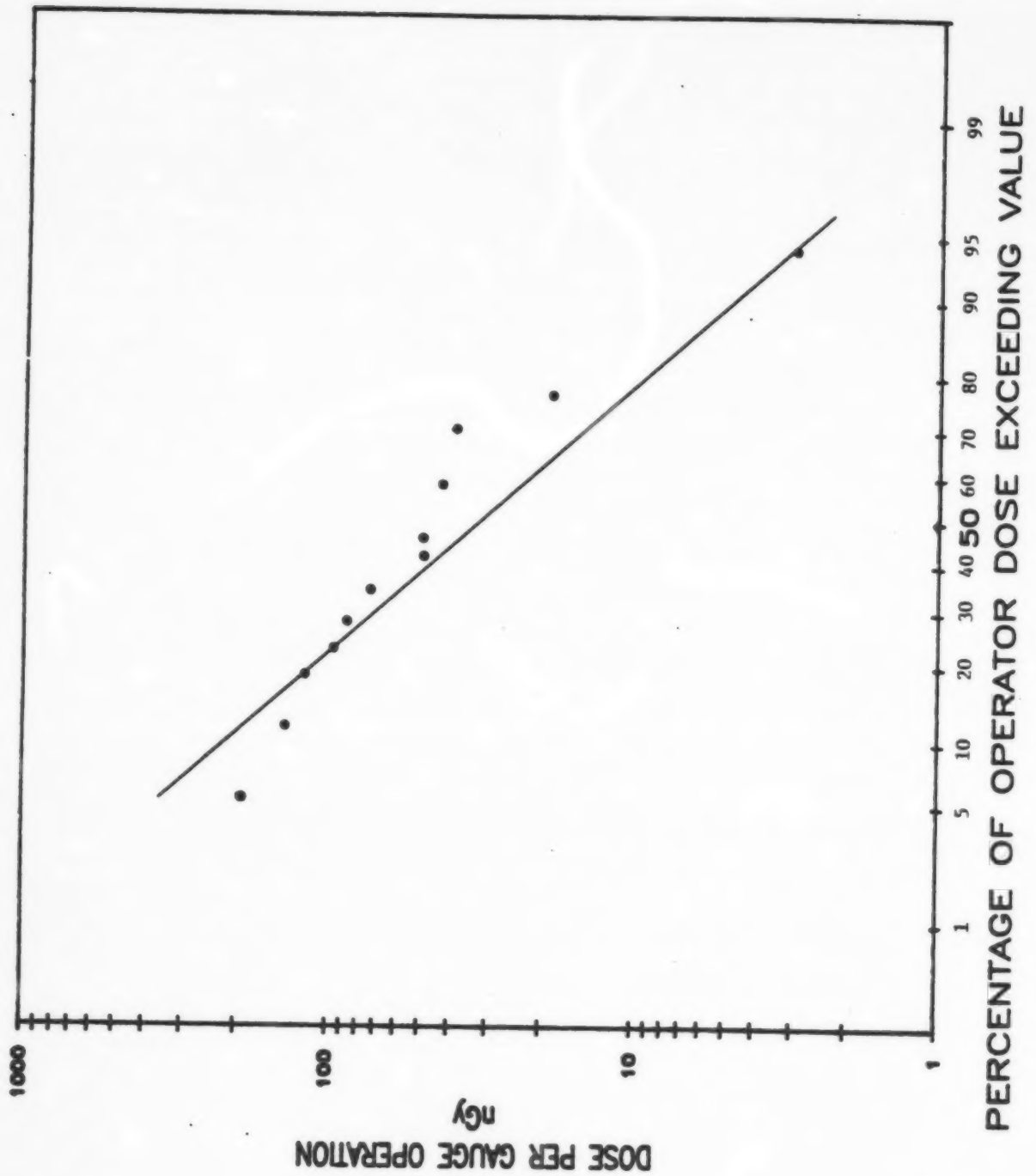


Figure 14: Doses to Moisture-Density Gauge Operators from Gauge Transportation

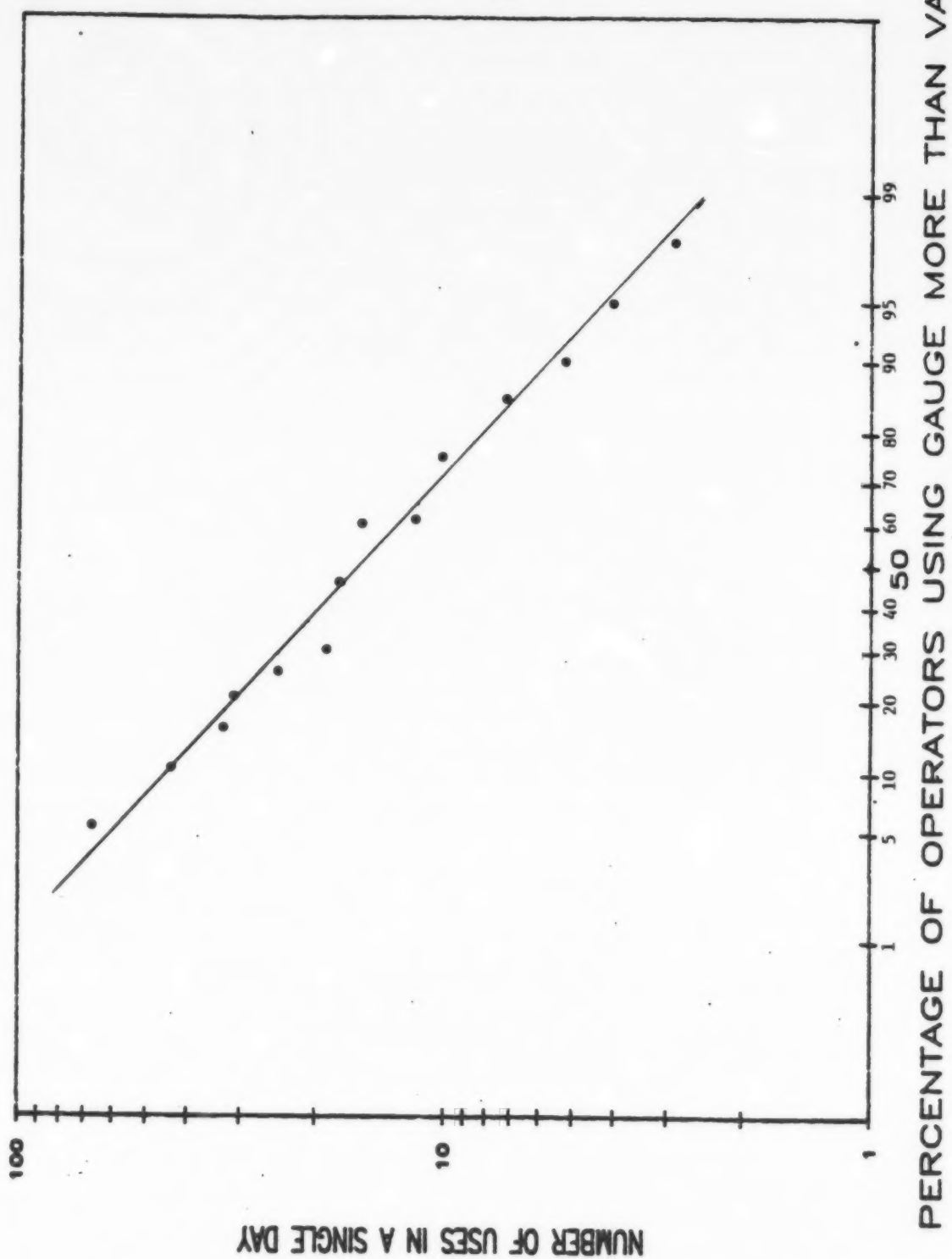


Figure 15: Number of Daily Moisture-Density Gauge Uses Among Field Study Operators

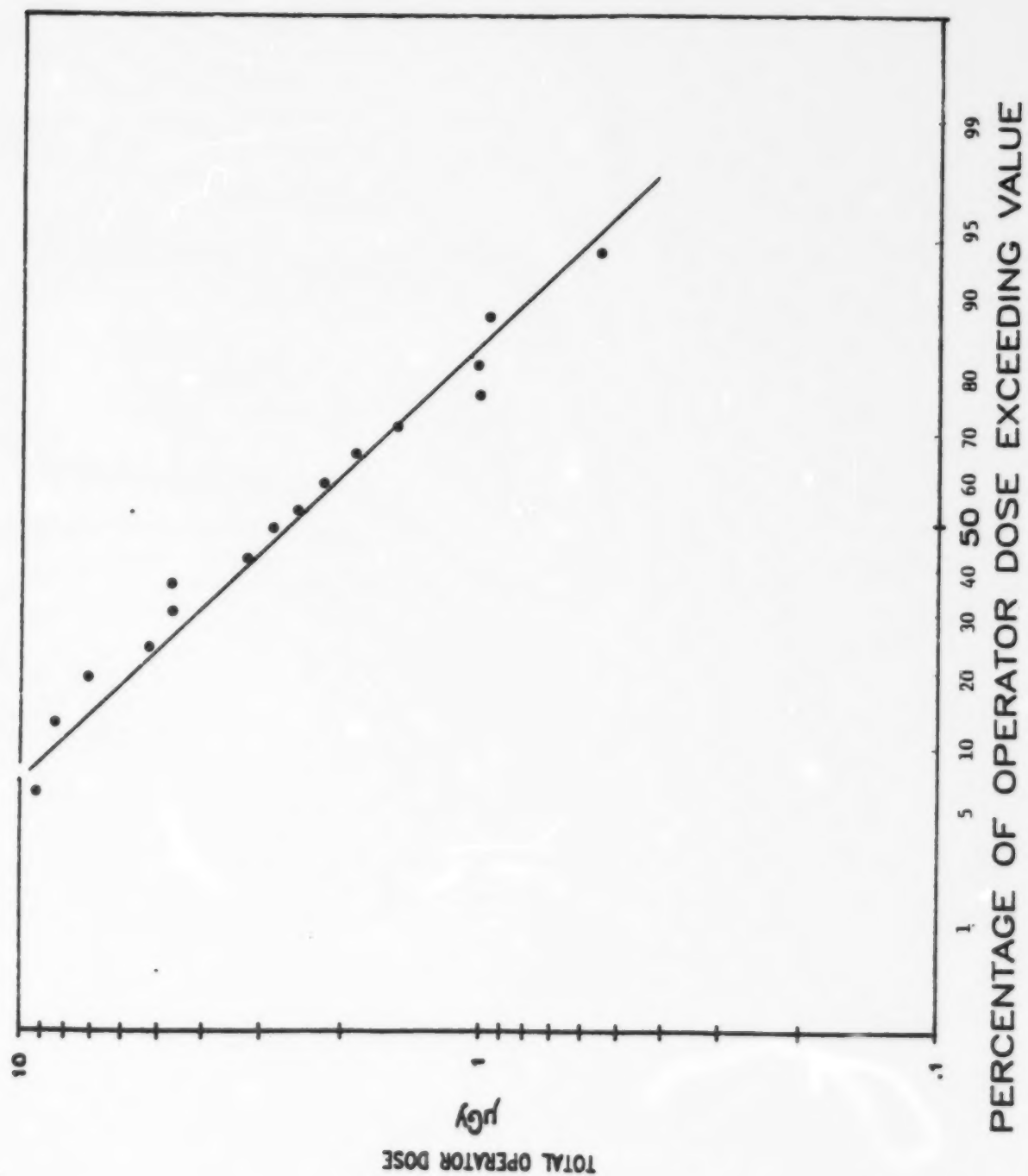


Figure 16: Distribution of Total Operator Dose Associated with the Operation of Portable Moisture-Density Gauges